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EVOLUTION OF THE DEPARTMENT OF DEFENSE MILLIMETER AND MICROWAVE MONOLITHIC INTEGRATED CIRCUIT PROGRAM

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ABSTRACT

The Millimeter and Microwave Monolithic Integrated Circuits (MIMIC) program had its origins in the concern of the smart weapons community for the affordable production of millimeter wave missile seekers, but the broad-based applicability of the technology to radar, communications, countermeasures, and counter-countermeasures was recognized in the formulation of the program. The program was initiated in the turbulent 1980s during the period of high technology trade deficits (and the defense buildup) that created an atmosphere of crisis leading to searching examinations of the reasons for the defeat of the United States in the global marketplaces.

The resultant initiatives by the Congress, the Executive and the private sector created a favorable climate for the execution of the program that featured a unique architecture in which goals were framed in system terms to provide the linking mechanism between materials research, device design, modeling simulation and testing leading to application in the four military application areas cited. The program provides a useful model that could be applied to other programs designed to achieve either civilian or military objectives.

The report traces the evolution of the technology from program formulation when the market was principally military to completion when the market was principally commercial, leaving the semiconductor industry well positioned to cope with the defense cutbacks and downsizing. The report concludes with an analysis of the elements that made the program a success.

SUBJECT TERMS

Millimeter Seekers; Gallium Arsenide; Microwave; Integrated Circuits; Millimeter and Microwave Monolithic Integrated Circuit (MIMIC); Smart Munitions; Radar; Communications; Countermeasures; Counter-Countermeasures; Field Effect Transistor (FET); Metal Semiconductor Field Effect Transistor (MESFET); High Election Mobility Transistor (HEMT); Hetrojunction Bipolar Transistor (HBT); Baseline Seeker; Manufacturing Methods and Technology (MM&T); Dual-Use Technology; Metrology and Standards; Global Environment; Science Policy

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I. INTRODUCTION AND SUMMARY

The purpose of this report is to trace the evolution of the Microwave and Millimeter Monolithic Integrated Circuit (MIMIC) Program and examine the elements of the program that made it a success. In order to tell the story completely, it is necessary to trace the formulation and execution of the program in the turbulent environment of the 1980s defense buildup and the beginning of trade deficits in the high technology industry including semiconductors. The program provided a unique architecture in which program goals were framed in system terms to provide the linking mechanism between materials research, device design, modeling, simulation, and testing leading to applications in four major areas of high technology: radar, communication, countermeasures and counter-countermeasures, and smart weapons. The program featured both structured and unstructured parts with feedback loops that generated the motive force for compressing the innovation process, thus providing a valuable model that can be applied to other military or civilian programs for achieving national objectives. Although the MIMIC program found application in four broad areas, it had its origins in the area of smart weapons; therefore, an additional purpose of this report is to present this early history that has not been treated fully.

The United States (U.S.) emerged from World War II as a world power with no rival in industrial might and scientific and technical leadership, but this led to complacency in the early postwar years. This complacency continued in the 1950s and 1960s, and did not disappear in the 1970s as trade deficits were mounting, since the Nation took comfort in the fact that it was the world leader in science and technology. However, the loss of the U.S. position in the global marketplace in high technology industries in the 1980s, brought about searching re-examinations of what was wrong with the entire product development cycle in various industry segments including semiconductors. In a 1988 report to the Secretary of Defense from the Under Secretary of Defense for Acquisition, the weakness in defense industrial competitiveness was attributed to flawed management theory and practices, the low status of manufacturing in American society, and inadequate attention of engineering schools in American universities to design and manufacturing. [1] The Executive Department, Congress, and the private sector launched a wide range of initiatives to cope with fragmentation of policy on the national level, correct weaknesses in educational institutions, encourage technology transfer, promote partnerships between public and private sector institutions, and fine tune the science policy framed by Vannevar Bush at the close of World War II. [2]

Section II of this report traces World War II origins and the flow of technical innovations in both hybrid Microwave Integrated Circuits (MIC) from the mid-1940s, to the early 1980s when the formulation of the MIMIC program began. An early effort to apply some of the emerging solid-state technology in a millimeter wave terminal homing missile seeker is described in Section III. This was the result of cooperative efforts between the Millimeter Wave Team at the Army Ballistic Research Laboratories, the Air Force Armament Directorate, the Electronics Technology and Devices Laboratory, and the Advanced Sensors Directorate at Redstone Arsenal, Alabama. The same year that laboratory and field-testing was conducted on the baseline seeker, a Manufacturing Methods and Technology (MM&T) program was formulated that led to a program that is presented in Section IV. The completion of the MM&T program in 1983, led to a study at the U.S. Army Missile Command (MICOM) of MICs and MIMIC Independent Research

and Development (IR&D) programs in the industrial base with the result that 40 companies were found to be working in the field, but projects in manufacturing process development were limited in scope.

The IR&D analysis was followed by a more detailed analysis that led to the establishment of the Monolithic Millimeter and Microwave Initiative (M^3I) Committee presented in Section V, along with MIMIC analyses conducted by other institutions presented in Section VI. In August 1984, the Advanced Sensors Directorate at MICOM was requested to provide technical and manufacturing cost data to the Office of Under Secretary of Defense for Research and Engineering. On 28 September 1984, this millimeter wave data was the subject of discussion at the Defense Systems Acquisition Review Council (DSARC) review of the Multiple-Launch Rocket System-Terminally Guided Submunition (MLRS-TGSM), an international program that featured a millimeter wave homing seeker. This review led to the establishment of the M^3I Committee to make a more comprehensive industrial base analysis presented in Section VI. As the work of the M^3I Committee progressed, the need for a structured program became better crystallized, (Section VII) and a number of MIMIC conferences served to further focus the program and highlight the key challenges (Section VIII). One of the key factors in the success of the program was the integration of metrology and standards with technology development.

The globalization of defense activities in which the MLRS-TGW program was formulated, and the loss of U.S. industry in the international marketplace led to a searching re-examination of U.S. science policy and an attempt to formulate a new one (Section X, XII). The MIMIC program bears the imprint of the Global Environment in the period in which it was formulated and executed. The sense of urgency created by the searching re-examination of what was wrong with the industry, as well as other industry sectors, was doubtless a contributing factor in the success of the program, but there was also great concern about protecting the U.S. interest while still maintaining competitiveness in the global market. The uniqueness of the environment in which MIMIC emerged makes it a valuable model for study. Section XI provides a summary of the program, and Section XIII presents the elements that made it a success. Section XI provides a summary of the elements that made it successful and that also make MIMIC a valuable model for study.

II. EARLY BACKGROUND

Achieving compact, low cost, and highly reliable electronic circuit functions was an objective as well as that of the radio proximity fuze program conducted under the supervision of the Office of Scientific Research and Development with the Navy responsible for the development of fuzes for rotating projectiles, and the Army responsible for non-rotating projectiles such as bombs, missiles and mortars. All the fuzes were based on the same principle of the Doppler effect, but each application presented unique design challenges in environmental effects, safe and arming, antenna radiation patterns and power sources. The tiny assembly that included miniature vacuum tubes, resistors, capacitors, and inductors were required to fit existing projectiles using the same space as the mechanical fuzes, without changing the ballistic characteristics of the projectiles. The development and use of the proximity fuze has been presented in a number of papers. [4 through 9]

The proximity fuze program conducted during World War II by the Ordnance Development Division of the National Bureau of Standards (NBS) and continued after the war, provided motivation for compact, integrated electronic subsystems that could be manufactured at low cost. The successful application of printed circuit technology to the radio proximity fuze during the war led the NBS to prepare a comprehensive treatment of printed circuit technology in anticipation of the peacetime applications. The processes used for applying conductors to an insulating surface fell in six categories: (1) painting, (2) spraying, (3) chemical deposition, (4) vacuum processes, (5) die stamping, and (6) dusting. Through numerous innovations in the first five categories, it was possible not only to apply conducting paths between circuit elements on a planar surface, but through process variations, fabricate resistors, capacitors, inductors and antennas, as well as printing portions of the circuit on the miniature and subminiature vacuum tubes, the principal active circuit element before the arrival of the transistor. The benefit of printed circuits was reduction of circuit wiring to two dimensions through printed circuit technology that also allowed a reduction in the number of labor-intensive soldering operations even in the smallest radio sets. One indicator of the intensity of the innovative activity in printed circuit technology is the number of patents cited in the Brunetti-Curtis Paper. [10]

Project Tinkertoy, initiated in 1953, was an outgrowth of the wartime work on the radio proximity fuze that was conducted by NBS in collaboration with industry under the sponsorship of the Navy. The objective of the program was to achieve both miniaturization of electronic assemblies and automation of the manufacturing process. The basic module was composed of five ceramic wafers with resistors and capacitors mounted on each of the flat sides of the wafers with printed silver conductors connecting the circuit elements. The wafers with attached components were then stacked one above the other with the top wafer formed to provide a socket for a vacuum tube. Although transistors were coming into wider use at the time the projected was initiated, Tinkertoy was never adapted for the arrival of the transistor which led to the demise of the concept. Further information on the project can be found in References 11 through 13.

A modified version of Tinkertoy emerged in October 1957, shortly after the Russians launched Sputnik when the Surface Communication Division of the RCA demonstrated a pen-size radio to the U.S. Army Signal Corps. The modified version of Tinkertoy was christened the Micromodule Program and received strong support from the Signal Corps which led to the demonstration of helmet radios and miniature computers in 1960. The micromodule featured transistors and smaller ceramic wafers with the top most wafer configured to support a vacuum tube; however, that feature was never used since transistors were in widespread use. [14]

Although both the Tinkertoy and the Micromodule Program were in a sense successful, Tinkertoy was overtaken by the invention of the transistor, and the Micromodule Program was overtaken by the invention of the integrated circuit by Noyce and Kilby. According to Kilby's patent:

> "It is possible to achieve component densities of greater than 30 million per cubic foot compared with 500 thousand per cubit foot, which is the highest component density attained prior to this invention." [12]

To provide continuity in the technology of electronics components miniaturization for defense application, the Army Diamond Ordnance Fuze Laboratory (DOFL) was formed in 1953 with the transfer of the Ordnance Development Division of NBS to the Department of the Army under the Chief of Ordnance to continue the fuze work. In 1957, DOFL won the Micro-Miniaturization Award for the Application of photolithographic production of the transistor. [15] In 1962, DOFL was renamed the Harry Diamond Laboratories with a broader mission under the Army Materiel Command (AMC) that was created that year. The Signal Corps and its successor, the U.S. Army Electronics Command, also played a pivotal role in working with industry in the development of miniaturization and micro-miniaturization of electronics involving the development of the transistor, printed wiring technology, and integrated circuits over the period of 1946 to 1964 that established the foundation for the semiconductor industry. Some of the key players in this effort were Stanislaus F. Danko, Frank Brand, James Meindal, Bernard Reich, Milton Tobman, and Leon Shumann. [16] In 1965, a group was formed under Vladimir Gelnovatch to provide a focus for the appointed manager of the Army MIMIC program.

The Post-World War II work by NBS, Centralab of Globe Union, the Navy, Air Force, and the Army Signal Corps led to a number of innovations that were available for integration with the transistor when it arrived. [17] In 1962, DOFL was renamed Harry Diamond Laboratories with a broader mission under the AMC created that year. The concept of the field effect transistor that would provide one of the key active devices for the MIMIC program had its origins in the work of William Shockley. [18] Shockley could later point to the page of his laboratory notebook, dated 20 February 1940, at Bell Telephone Laboratories as the first record of the Schottky field effect transistor:

> The invention of Figure 4(b) was theoretically sound.
> It describes a device of the type now known as a
> Schottky – gate field effect transistor. [19]

The formulation of an Ad Hoc Group in the Defense Department Research and Development Board (RDB) gave recognition to the potential impact of transistors on military systems. This led to the formation of a Sub-panel on Semiconductor Devices under the RDB's Panel on Electron Tubes. In his paper on the invention of the integrated circuit, Jack Kilby gives credit to G. W. A. Dummer of the Royal Radar Establishment as the first to perceive the possibilities of circuit integration based on semiconductor technology in 1952, in an Electronics Components Conference:

> "With the advent of the transistor and the work in semiconductors generally, it seems now possible to envisage electronics equipment in a solid block with no connecting wires. The block may consist of insulating, conducting, rectifying and amplifying materials, the electrical functions being connected directly by cutting out various layers." [17]

These words are suggestive of the monolithic approach on which MIMIC is based that implies that both the active and passive components including the transmission medium are fabricated on a common semi-insulating substrate. A second concept included in the term MICs is one in which a planar transmission medium capable of being printed on a dielectric substrate provides the integrating structure for discrete active and passive components attached to it. This is the hybrid approach to integration that is referred to as hybrid-MICs, or more commonly, MIMICs. The experience gained in the development of MICs, or hybrid-MICs, provided a foundation for maturing the monolithic technology or MIMIC. Harlan Howe has provided an excellent historical review of the technology. [20] The progress in MIMICs was built on advances in materials growth and characterization, active and passive device development, transmission line media, manufacturing process development, design modeling and simulation that began in the early 1950s, and was mature enough in the early 1980s to allow the formulation of the MIMIC program.

R. M. Barrett of the U.S. Air Force observed in the early 1950s that planar transmission media fabricated by low-cost printed circuit techniques could be extended to allow both passive and active circuit functions to be coupled together to provide a complete receiver. Barrett visualized the symmetrical flat transmission line as an evolution of the coaxial transmission line obtained by flattening both the inner and outer conductors into rectangular shapes and then removing the sidewalls of the outer conductor. [21] Barrett credits V. H. Rumsey and H. W. Jamieson with the first application of the symmetrical stripline as a power division network in World War II. Barrett was active in promoting the application of the stripline as a low-cost alternative to the heavy hybrid junctions and waveguide components in airborne radars and communication equipment, and also observed that:

> "It seems quite possible that the entire RF circuitry of a microwave receiver could be constructed by this method (printed circuit etching techniques)." [21]

There were other innovations that contributed to the unfolding of the technology in the 1950s. In a personal communication, Gelnovatch recalls these early years of research on transmission media, and the contributions of Ardeti of ITT, and George Gobeau at Signal Corps Engineering Laboratories (SCEL). According to Gelnovatch who worked with George Gobeau:

> "Gobeau did propagation experiments, one of them being launching waves into a dielectric coating over a ground plane without the aid of a center string transmission line. Later in the 1980s when researchers were investigating higher modes in microstrip, lo and behold they found that the first higher order TE mode (or was it the TM mode) was really the Gobeau mode." Gelnovatch also recalled that it was H. A. Wheeler who characterized microstrip. "He did a multi-dielectric analysis of the non- Transverse Electromagnetic Mode (TEM) mode in microstrip using his 'filling fraction' method to approximate TEM propagation. This gave researchers the first handhold on relating impedance, dielectric constant, and W/H ratios that allowed reliable design. Tables and charts of this work were published in the Microwave Journal Handbook in the late 1960s."

The microstrip line was introduced by Greg and Engleman to provide adaptability for wide-band communication power level components that demonstrated zero dispersion over a band of frequencies from 20 GHz to 10 GHz. [22]

In the late 1950s, a major challenge in making the region of the electromagnetic spectrum between 30 GHz and 300 GHz more broadly applicable beyond its early use in spectroscopy and materials research was achieving adequate levels of power. The launching of Sputnik in October 1957, provided an additional stimulus for research in electronics miniaturization sponsored by the Department of Defense (DoD), and one effect was to put the focus on millimeter wave technology. An early indication that a broader vision for millimeter waves was beginning to crystallize occurred at the Symposium on Millimeter Waves at the Polytechnic Institute of Brooklyn on 31 March, and 1 to 2 April 1959, but no solid state millimeter source appeared as a topic on the program.

The office of Naval Research, the Air Force Office of Scientific Research, and the U.S. Army Signal Research and Development Laboratory were co-sponsors of the event, and representatives from these agencies gave brief greetings with forecasts for millimeter waves. The two sessions devoted to millimeter wave power generation gave a clue that millimeter wave was emerging as a technology of importance for both military and civilian applications. Also in April 1959, an integrated circuit concept was announced at the Institute of Radio Engineers (IRE) show in which both active and passive devices are processed on one wafer of silicon and provided with interconnections between circuit functions.

There was also vigorous research in the 1950s and early 1960s, on providing the theoretical foundations and manufacturing methods for microwave semiconductor devices, particularly two-terminal devices. The 26 papers in "Selected Papers on Semiconductor Microwave Electronics" edited by Sumner N. Levine and Richard R. Kurzrok, concentrated on the use of the p-n junction

to achieve amplification and frequency conversion of microwave frequencies. Included were 14 papers on parametric amplifiers, 4 papers on tunnel diodes, 4 on general theory of non-linear elements, 3 on fabrication, and 3 general survey papers. [23] One of the general survey papers was "Semiconductor Devices for Microwave Applications" by Milton Tenzer, U.S. Army Signal Research and Development Laboratory. The discovery of the phenomena on which the tunnel diode depends by Leo Esaki in 1957, the IMPATT diode or transit time diode in 1958 by Read, and the Gunn effect diode in 1963 by J. B. Gunn, provided the stimulus for developing the technology of two-terminal devices that could operate in the microwave and millimeter wave region. Esaki reported that it was very easy to make a Radio Frequency (RF) oscillator in the early days "without much effort" [24]. The transfer of electrons from a high-mobility conduction band to a low-mobility sub-band provided the physical basis for the differential negative resistance in the Gunn effect in gallium arsenide. Oscillators based on this effect were low noise. Progress was rapid in extending the frequency into the millimeter wave region with increasing power levels. Although the first IMPATT diode was not fabricated until 1964, by the late 1960s power output was increasing at the rate of 2 watts per year. [25] In January 1966, the *IEEE Transactions on Electron Devices* devoted a special issue to Gunn effect devices, avalanche transit time devices, and microwave radiation from indium antimonide. [26] The Gunn diode, IMPATT, the varactor, and the tunnel diode were the two terminal devices that provided the transmit-receive functions for early work in smart munitions development. The conflict over the invention of the integrated circuit was resolved and Jack S. Kilby and Robert N. Noyce shared honors for the achievement.

Hybrid microwave and millimeter wave integrated circuits achieved greater maturity with advances also made in the 1960s in miniature guided wave structures in both microwaves, millimeter waves and optics as the vehicle for integrating small and rugged circuit functions into subsystems. S. E. Miller's paper "Integrated Optics: An Introduction," was published [27]; the slot line characteristics were described by S. B. Cohn [28]; and the characteristics of the coplanar waveguide were presented by Wen. [29] Drawing on the work of Marcatelli, Knox, and Toulios saw the potential of the high permittivity dielectric image line offering the prospect for lower propagation loss for millimeter wave integrated circuits than the microstrip line. [30] The Symposium on Submillimeter Waves held at the Polytechnic Institute of Brooklyn on March 31, and April 1 to 2, 1970, provided an excellent review of the state-of-the-art in millimeter and submillimeter waves at the close of the decade of the 60s. [31] However, transmission line media received limited attention and the only semiconductor devices appearing on the program for power generation were the Gunn and IMPATT diodes. [32, 33]

At the symposium cited, Skolnik presented the useful characteristics and limitations of millimeter and submillimeter waves, and identified 47 potential applications in radar, communications, radiometry, and instrumentation. Skolnik noted that the relatively poor status of components was well documented, but even if the limitations of millimeter wave components were overcome, the limitation of small antenna apertures and high losses would remain. Although a microwave radar had been demonstrated in Germany in 1904, it was the maturing of the airplane in the 1930s that created a real need for microwave radar that provided the stimulus for extensive advancement in microwave technology. According to Skolnik, the economic benefits of millimeter waves for specific applications was yet to be examined. [34]

A. Hybrid MICs for Radar Applications

The first efforts to advance the art of MICs in silicon by Texas Instruments under the sponsorship of the Air Force Molecular Electronics for Radar Applications (MERA) program began in 1964, and by late 1968, 600 radar Transmit/Receive (TR) modules had been fabricated. Although the initial focus of MERA was on advancing the art of microwave integrated circuits, the program eventually led to the first demonstration of a solid-state array radar at x-band based on silicon processing technology. The T/R module was MIC technology built in alumina microstrip using thin film techniques and featured an S-band preamplifier, two-phase shift networks, 2 times 4 multipliers, a pulse amplifier, a T/R switch, a mixer, and a preamp. [20, 35] The MERA work was apparently the stimulus for a series of T/R module studies [36, 37, 38, 39], and intensive development of MIMIC technology. A decade of progress in millimeter and microwave integrated circuits was featured in three special issues of the IEEE MTT-S Transactions devoted to microwave integrated circuits over the decade from 1968 to 1978: July 1968, July 1971, and October 1978.

The special issue of the *IEEE Transactions*, Vol. MTT-16, No. 7, July 1968, edited by Sy Okwit, was a signal that the stage was being set for a revolution in microwave and millimeter wave technology. In the lead article, "Integrated Microwave Modules – A Prospectus" [40], William Webster observed:

> "There is also a premium on size, weight, and power in airborne applications. These factors are the main reasons for the intensive early interest on the part of the Air Force. By far, the biggest segment of the microwave business in the easily foreseeable future is radar."

Although research was in progress on millimeter wave integrated circuits at 94 GHz [41, 42], the technology was much less mature than the lower frequency bands. The insight that this technology would make smart weapons feasible emerged with the recognition that discrete Gunn and IMPATT oscillators could provide the basis for solid state transceivers that could be packaged in a 6-inch diameter missile. The demonstration of molecular beam epitaxy by Cho and Arthur at Bell Telephone Laboratories in 1969 [43], and U.S. Patent 362257 *Semiconductor Device with Superlattice Region*, issued to Esaki, Ludeke, and Tsu set the stage for much research in the 1970s [44] and provided the foundation for advancing three-terminal devices such as MESFET and HEMTS.

B. The Emergence of the GaAs MESFET and Monolithic GaAs Integrated Circuits

The superior properties that GaAs offered as an alternative semi-insulating substrate with suitable dielectric properties for forming microstrip transmission lines between circuit functions was soon recognized and became the leading candidate material. In 1966, Mead reported the desirable features of a GaAs Field Effect Transistor (FET) using a Schottky barrier gate. [45] In 1967, Hooper and Lehrer reported the characteristics of an epitaxial GaAs field-effect transistor. [46] In 1968, Mehal and Wacker fabricated Schottky barrier diodes, Gunn

oscillators, varactor diodes, and tunnel diodes in planar form in semi-insulating GaAs using the epitaxial selective growth method and the mesa etching method. The application of the two Schottky barrier diodes to form a balanced mixer in conjunction with the Gunn local oscillator provided the basis for a RF receiver front end at 94 GHz. [42] By the early 1970s, the promise of the GaAs FET as a low-noise microwave transistor capable of extending the useful frequency range by more than a factor of two over existing silicon transistors for variety of circuit functions was widely recognized. In 1976, Pengelly and Turner reported the first broadband FET amplifier. [47] In his 1976 report on recent and current work in microwave FETS, Charles A. Liechti, included a bibliography of 250 references. [48] In 1978, DiLorenzo reported that over 250 papers had been published on the GaAs since 1970 [49]. In 1978, U.S. Patent 4,163,237, *High Mobility Multilayered Hetrojunction Devices Employing Modulated Doping* was issued to Raymond Dingle, Arthur C. Cassard, and Horst L. Stormer of Bell Telephone Laboratory. [50] In 1979, DiLorenzo and Wisseman reported that over 350 papers on the GaAs MESFET had been published since 1973, and gave the first comprehensive state-of-the-art review of the GaAs MESFET as a power amplifier. [51]

C. Development of MICs and MMICs by Army Laboratories

1. Ballistic Research Laboratories (BRL)

The work of the Millimeter Wave Team of the Army BRL at Aberdeen Proving Ground, MD was an integral part of the development of millimeter wave technology. This team under the leadership of Richard McGee began, about 1960, a wide ranging program of research not only in phenomenology of both active radar and passive radiometric systems, but the development of components and instrumentation that provided the technological foundation for millimeter wave seeker development. This in-house research led to the development of laboratory demonstration models of the first all-solid-state radars operating at 35, 45, 140, and 240 GHz. By 1969, the feasibility of tracking a target in a complex background with a radiometer featuring a scanning antenna was also demonstrated. This was followed by a guidance radiometer demonstration at 35 GHz that provided the foundation for the MICOM Terminally Guided Submunition (TGSM) design. Among the BRL pioneers in the development of millimeter wave radiometry were Victor W. Richards, Kenneth A. Richer, and Richard A. McGee. [52] In conjunction with a periodic analysis of the state-of-the-art in component and device technology, missile guidance concepts were developed and analyzed for application to direct fire close combat, including millimeter command and beamrider, air-to-ground, air defense, and fire support. To accomplish this research, specialized instrumentation had to be developed that required collaboration with the Fort Monmouth Laboratories.

The phenomenology research included target scattering, multipath effects, backscatter from ground clutter, atmospheric attenuation, attenuation and backscatter from rainfalls. Carefully designed experiments established quantitative relationships between the rain characteristics (rainfall rates, drop size distribution) and the attenuation and backscatter from the rain at 9.375, 35, 70, 94, 140, and 225 GHz over a wide range of rainfall rates. From this research through the end of the 1960s, Richer concluded:

> "From the broad series of propagation measurements made to date, however, a general picture begins to emerge. One should be able to operate short range (possible 10 or more km) radars in the 35, 94, 140, and 225 GHz regions except for heavy rainfall and fog conditions at the two higher frequencies. Short range (1 to 2 km) radiometric systems should be feasible at 35 and 94 GHz; possibly only relatively cloudless days at 94 GHz. However, the extremely high resolution and potentially small size systems at millimeter wave lengths are attractive even for such relatively short ranges of operation. Further, millimeter wave techniques are extremely valuable for measurement of the environment itself." [53]

This research by Richer and his group on propagation effects established the broad boundaries on what was achievable in the millimeter region for missile guidance. [53,54,55,56] This early work in "passive" and "active" radiometry by the Army, Air Force, and Sperry led to sensing options that were part of the first source selection for millimeter wave seekers held at Aberdeen Proving Ground in 1972. The first generation 35 GHz millimeter wave seeker that emerged from this process is shown in Figure 1.

From the results of the propagation research and the risk in component and device development above 100 GHz, plans for guidance subsystem development above 100 GHz at MICOM were dropped. This decision was also responsive to a request from the Electronics Technology and Devices Laboratory (ET&DL) that MICOM needs for ET&DL work be prioritized.

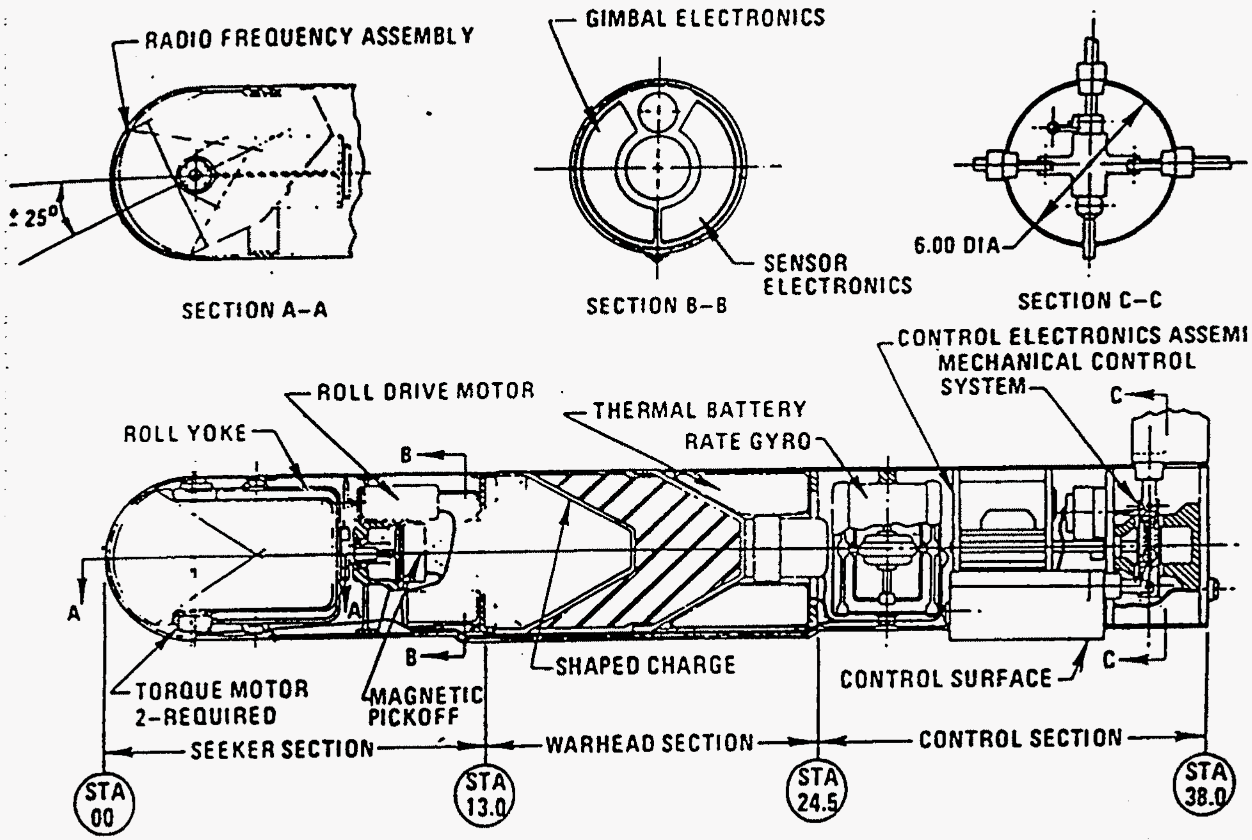

Figure 1. First Generation Millimeter Wave Seeker (Courtesy BRL)

2. Fort Monmouth Laboratories

The U.S. Army Signal Corps was on the forefront of major technical innovations from the date of its founding on 21 June 1860, by Albert James Myer, the first signal officer, and this tradition was continued in the Signal Corps Engineering Laboratories at Fort Monmouth, NJ that played a vital role in winning World War II. In the post-World War II period, the laboratories led an effort in miniaturization and micro-miniaturization of Army communications - electronics. In a sense, it was the Signal Corps Engineering Laboratories that launched the nation into the missiles and space age in the early post-World War II period. William Stroud of the Laboratories led the development of a scanning system for the Vanguard satellite. Signal Corps scientists using a SCR-271 long-range radar bounced radar signals off the moon on 10 January 1946. The announcement of the "Dick Tracy" *Transistor Wrist Radio* by the U.S. Army Signal Corps Laboratories in 1953, not only attracted wide-spread public interest, but alerted the defense community to the high potential of the new invention for a variety of applications. The Army encouraged the inventors to file a patent application and explore the commercial applications - perhaps a signal that the concept of "dual-use" technology was taking shape. The Laboratories not only pursued a search for transistor applications, but maintained a program of fundamental research to achieve a better understanding of the physics of materials and devices and develop the manufacturing process technology for the devices. In 1958 and 1959, the Signal Corps Engineering Laboratories made a major payload contribution to the Vanguard satellite program, and on 18 December 1959, in collaboration with the Air Force, launched the first communication satellite under Project SCORE (Signal Communication via Orbiting Relay Equipment).[57]

In 1965, a group was formed under Vladimir Gelnovatch in the Electronics Component Laboratory to provide a focus for the development of hybrid microwave integrated circuits. The program of research in this group included a broad range of microwave circuit techniques, both distributed and lumped to provide the foundation for integration of the advances in solid state microwave devices. This included the investigation and ranking of several transmission lines including microstrip suspended substrate line, slot line, and coplanar waveguide. Materials technology for substrates, conductors, and dielectrics was a key part of this effort, and provided the foundation for development of design methodology that took into account the need to achieve a balance between performance, yield, cost, and reliability. One illustration of technology was demonstrated through the computer-aided design of wide-band integrated microwave transistor amplifiers on high dielectric substrates. [58] Strong emphasis was placed on efforts to employ digital computer technique to automate the design process, and one program was developed that optimized 24 variables in 383 seconds running time. [59]

By the time the Electronic Technology and Devices Laboratory was established in 1971, the foundation for the design of hybrid integrated microwave circuits had been established at the lower microwave, and the performance of lumped circuit elements was found to give performance as good as distributed elements up to 6Ghz. A principal challenge was to achieve integration at the higher frequencies where active devices were available, but the technology for integration was not. [60] In the meantime, the availability of two-terminal sources of microwave and millimeter power led to the conception of simple transceivers that

made use of these devices that could be packaged in 6-inch diameter missiles. ET&DL had supported this application with exploratory development funds for Gunn and IMPATT diodes. Closer communication evolved between ET&DL and the Laboratory at MICOM that gave a sharper focus to the application of MIC and MIMIC to smart weapons applications.

At the close of the 1970s, ED&DL had plans to invest approximately 6 million dollars overall in microwave technology, and about 3 million dollars in millimeter wave technology. The program had a thrust that provided for "Low-cost practical millimeter wave devices (35 to 600 Ghz) and nano second pulsers for target location and identification systems capable of all weather operation through battlefield ECM." [61] The solid-state devices program apportioned an average funding of 4 million per year toward low cost millimeter wave components for high resolution radar; missiles and projectile terminal homing; wideband SIGINT receivers; secure communications; all-weather capability; and penetration of battlefield obscurants. [62] The ET&TL was not only exploiting opportunities in MIC technology, but also focusing on monolithic technology based in gallium arsenide with the Field Effect Transistor as the active element at the higher millimeter wave frequencies. A strong in-house program was complemented by a diversified research program in industry. [63, 64]

As the need for a DoD-wide program in millimeter wave technology began to crystallize in the early 1980s, ET&TL was in a strong position to influence the structure of the program, particularly at the higher millimeter wave frequencies, since its wise investments in research and technology development over the prior 15 years was now ready for transition into applications in communications, radar, smart weapons, and countermeasures and counter-countermeasures. The pace of activity intensified following the formulation of the M^3I Committee by Under Secretary of Defense James Wade in 1984 as the first step in initiating a national program. ET&DL was represented on the committee by Vladimir Gelnovatch, Hans Hieslmair, Lothar Wandiger, and James Kesperis. By 1987, ET&DL and industry had achieved a W-band transceiver in MIMIC technology that set the stage for a MIMIC transceiver at that wave band. [65] The complementary features of MIMIC and VHSIC were provided by Thornton in Reference [144].

In October 1992, the Army Research Laboratory (ARL) was activated and ET&DL became an element of the laboratory. The management of MIMIC program for the Army continued in ARL through program completion in 1995.

III. THE BASELINE MILLIMETER WAVE SEEKER

The work of the Millimeter Wave Team at the Army Ballistic Research Laboratory in phenomenology, radiometric sensing, and solid-state radar development led naturally to the formulation of missile seeker concepts utilizing this technology. However, the high cost of millimeter wave components in the late 1960s and 1970s, led system developers to consider the use of the components for dual functions in a millimeter radar and radiometer integrated in one instrument to achieve improved reliability and performance. Such an instrument has been described by Foiani and Pearce that featured a Frequency Modulated-Continuous Wave (FM-CW) radar combined at 3.2 mm with a Dicke-type radiometer. [66] This concept provided the basis for the first millimeter wave seeker referred to as the baseline seeker. However, as higher frequency operation was achieved, it was found that the radiometric mode was of limited value above about 40 GHz, and was dropped after experience was gained at 94 GHz.

The availability of two-terminal solid-state sources of microwave power in 1970s (Gunn and IMPATT diodes), made it possible to conceive a transmitter-receiver unit that could be packaged as part of a millimeter wave missile seeker in a 6-inch airframe. The favorable results of a joint Army-Air Force evaluation of passive microwave radiometry in 1971, led the Ballistics Research Laboratory to issue a technical requirement for fabricating three millimeter wave/seekers capable of operating at 35 GHz in both the passive and active mode. MICOM provided funding and technical guidance for the program that led to a contract with Sperry Microwave. An early version of the first generation seeker is shown in Figure 2. The Sperry Microwave design featured a transmitter-receiver unit, with a conically-scanned antenna, target acquisition and tracking processor, and a two-axis gimbal that allowed the seeker to search, acquire, and track targets and provide steering signals to cause the submunition to impact the target. [67] Sperry fabricated three engineering prototypes, the first of which was configured for captive flight-testing in the Airborne Instrumented Millimeter Measurement System, at Redstone Arsenal, AL. The other two seekers were configured for a 6-inch diameter TGSM airframe, and ultimately one of these was converted to 94 GHz with the same circuit configuration as the 35 GHz seeker.

The seeker was capable of search in the active mode with a cone angle of 8.7 degrees, and track in both the active and passive mode. The basic concept featured dual-mode operation with the active mode for target acquisition and track to the terminal phase, then switchover to the passive or radiometric mode to obtain more stable centroid tracking. After the submunition is ejected from the launch vehicle, the active mode is initiated with FM-CW radar mode until the ground is acquired. An area search of the ground is then initiated in the active mode until a target is located, at which time target tracking begins providing signals to guide the submunition into the target. At some pre-selected terminal range, angle tracking in the active mode is switched to angle tracking in the passive mode to provide a more stable tracking centroid as the submunition closes on the target. [56] Massed battle tanks and armored personnel carriers were the intended targets of the submunition that could be attacked in partially obscured conditions unfavorable to optical and infrared sensors.

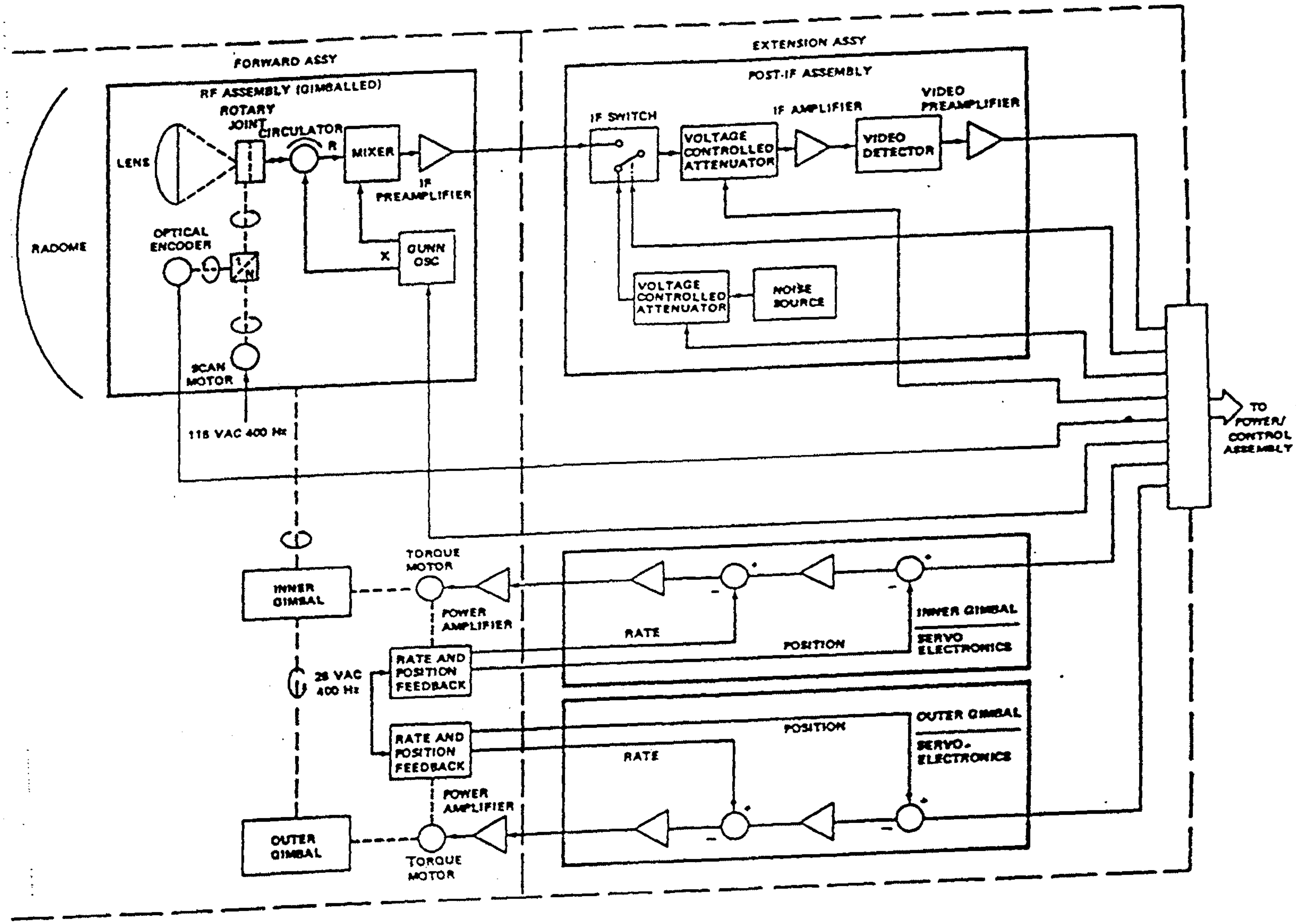

Figure 2. Block Diagram of Microwave Radiometric Seeker Subsystem [68]

Comparative evaluation of 35 GHz and 94 GHz seekers was performed at Redstone Arsenal in 1974 to 1975. [68] Under Air Force sponsorship, they were also evaluated in both tower and captive tests at Eglin Air Force Base. The prototype seekers were capable of operating in: (1) the active FM-CW mode, (2) the active noise illumination mode, or (3) the passive mode. The stabilization and control circuitry to provide integration with a missile airframe was not part of the delivered prototype seekers. Figure 2 shows the prototype seeker configured for testing at Redstone Arsenal. [68] Propagation effects were not considered in comparing the performance of the seekers in the two-millimeter wave bands, and the limited availability of radar target cross-section data in the two bands did not allow a complete comparative analysis at the time.

Two performance measures sought in the evaluation of the two-millimeter wave band were the detection range and the reliable tracking range in the active seeker modes. Figure 3 provides a comparison of the two seeker subsystems. The available power at 94 GHz was only 40 percent of that at 35 GHz, but the reduction in antenna beam with 94 GHz reduced the illuminated clutter area thus offering the potential for offsetting the lower power and higher losses. Although component losses in the two bands were not assessed at the time, it was recognized that losses would be substantially higher at 94 GHz, and the technology was much less mature. The results of this comparative seeker evaluation provided a stimulus for the ET&DL to focus on maturing millimeter wave technology at 94 GHz. Plans were in place to undertake MM&T projects on the seeker following the comparative evaluation of 35 Ghz and 94 Ghz seekers. [69, 70]

Characteristic	Symbol	MRSS-35	MRSS-94
Transmitted Power	P_t	50 mW	20 mW
Antenna Aperture	D	12.5 cm	12.5 cm
Noise Figure	NF	7.5 dB	9.0 dB
Receiver Aperture Efficiency	η	0.7	0.7
Wavelength	λ	8.6 mm	3.2 mm
Predetection Bandwidth	B	500 MHz	300 MHz
Tracking Loop Bandwidth	b	5 Hz	5 Hz
Conical Scan Fraquency	C_f	100 Hz	100 Hz
Center Frequency	F_c	35.0 GHz	94.0 GHz

Figure 3. Characteristics of the Microwave Radiometric Seeker Subsystem (MRSS) [68]

IV. MANUFACTURING METHODS AND TECHNOLOGY PROGRAMS

The baseline seeker developed by Sperry Microwave provided the design on which the first manufacturing process development conducted on a millimeter wave seeker was conducted. Sperry was able to draw on extensive developmental experience in conducting a two-phase MM&T project on the Assault Breaker Phase II Drop Test Seeker (the baseline seeker). Under Phase I, the procedure was to start with the baseline seeker design and establish the criteria for comparing manufacturing processes, assembly techniques, inspection procedures, configuration, and test procedures. [71] From this, actual costs of the baseline design were obtained and the cost drivers identified. Alternate approaches were then developed to reduce the impact of the cost drivers in the following areas: material substitution, configuration change, tolerance studies, fabrication techniques, fixtures, procedures, and tests. From this process, Sperry concluded that a cost-effective approach could be developed that would allow a production rate of 800 transceiver units per month with current (1982) technology at a cost of 2,300 dollars per unit (Fig. 4). This process flow summary for Phase I is shown in Figure 5. The production cost analysis of the baseline seeker showed that 80 percent of the RF Front End Section was contained in major component development.

Type of Realization	Unit Production Cost Estimate	Relative Volume	Production Availability
Discrete Component	$14,000	26 in^3	1978
Semi-Integrated	$ 6.500	9 in^3	1979
Fully Integrated	$ 2,300	6 in^3	1984
Monolithic	$ 900	1 in^3	1986-88

Figure 4. W-Band RF Front End Evolution for an FMCW System [71]

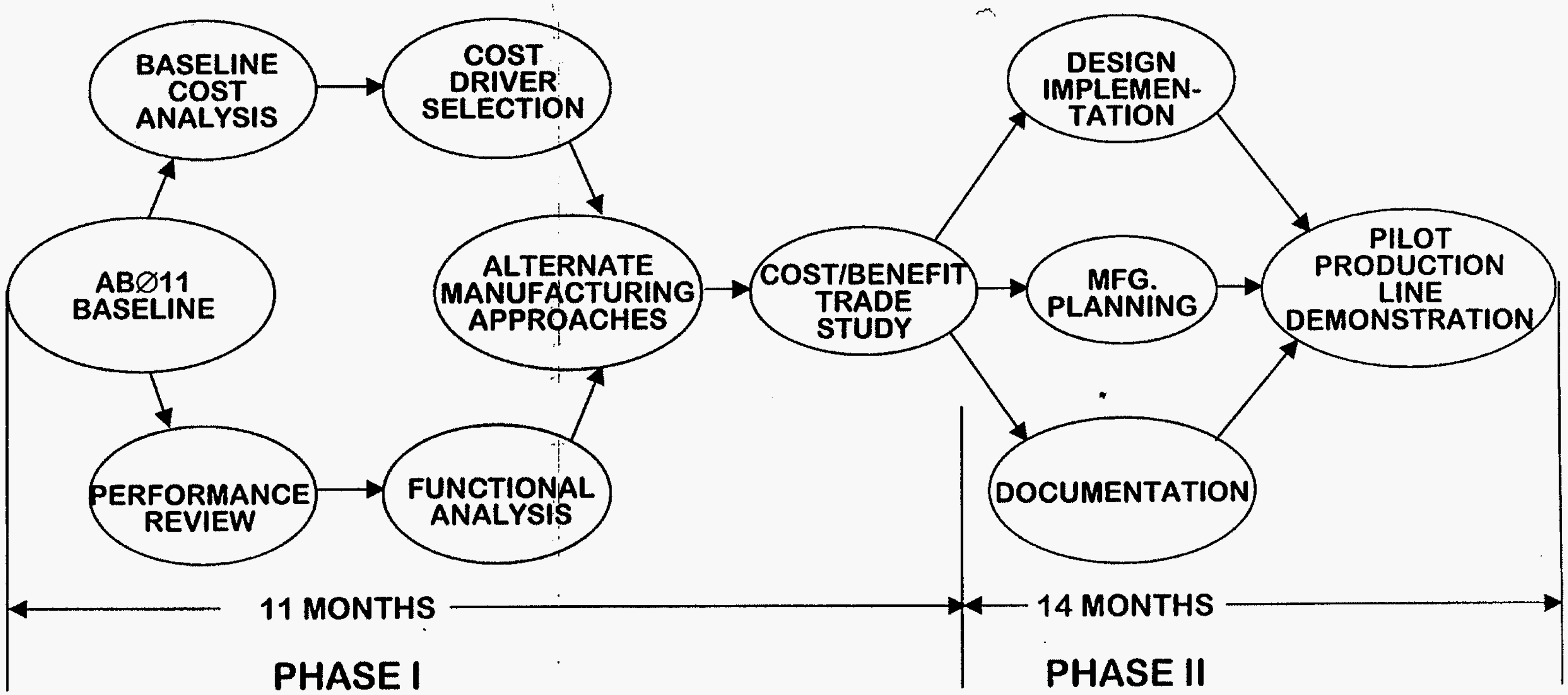

Figure 5. Producibility Engineering and Planning Flow Diagram for the Assault Breaker Phase II Drop Test Millimeter Seeker [72]

Under Phase II of the MM&T project, an alternative configuration of the seeker front end was developed that was referred to as the Producibility Engineering Planning Configuration (PEP'd). [72] In this configuration (Fig. 6) the parts count was 37 percent less than in the Baseline configuration. This was accomplished by eliminating the interconnecting waveguide assemblies allowing ease of assembly and interchangeability of the RF source, isolator, mixer-IF-amplifier, and duplexer. The circuit diagram of the RF front end and antenna assembly is shown in Figure 7. Both the radome and parabolic reflector in the baseline configuration were machined from REXOLITE, a non-moldable plastic. In the PEP'd configuration, these parts were injection-molded from NORYL.

Five millimeter seeker heads were produced in the Pilot Production Line phase of the project, and an industry, Government demonstration was held in Clearwater, Florida on 25-26 January 1983. [72] This phase of the program was a valuable learning experience, since the change from the Baseline Configuration to the Planning Configuration led to an entirely new technical data package; substantial product development took place during the manufacturing cycle. It was determined early in Phase I of the program that the RF components and the antenna assembly represented 79.7 percent of the unit production cost of the Front End Section. The cost of the same components in the PEP'd configuration showed that the same components represented 60 percent of the unit production cost, or a 19.7 percent reduction. [72] This was attributed to the "fully integrated" RF component design approach that led to the significant parts count reduction. (The term "fully integrated" means "millimeter integrated circuits" or hybrids.)

Sperry concluded that the greatest impact on unit production cost of the RF front end could be achieved by the introduction of monolithic millimeter and microwave integrated circuits, but for Sperry this would involve an IR&D investment of 8 to 10 million dollars over a 5- to 8-year program [72], woefully inadequate to pay for new capital facilities, research on device physics, MIMIC design tools, improvements in materials quality, and manufacturing process development. The Sperry conclusions led naturally to the question: "What is the magnitude and content of the IR&D industrial base and the DoD funded technology base in industry?" The answer to this question will be discussed in the following two sections.

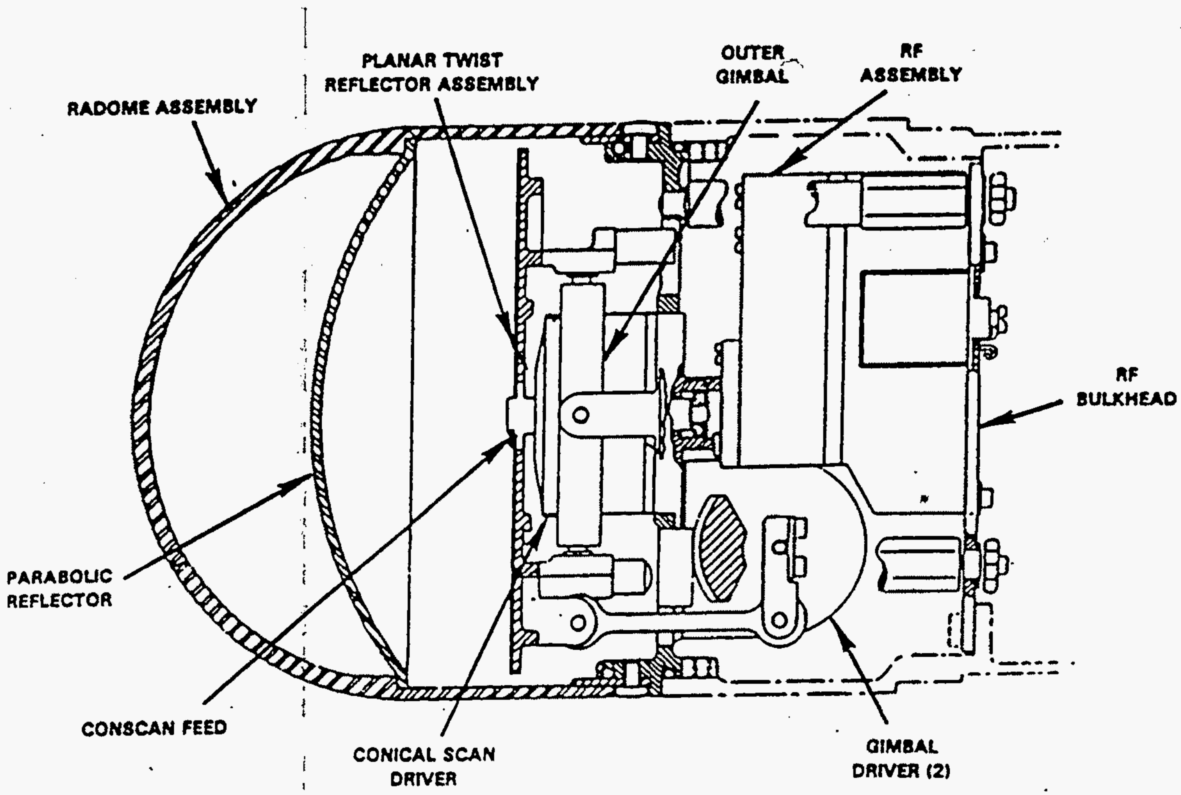

Figure 6. Millimeter Wave Front End for the Producibility Engineering Planning Configuration [72]

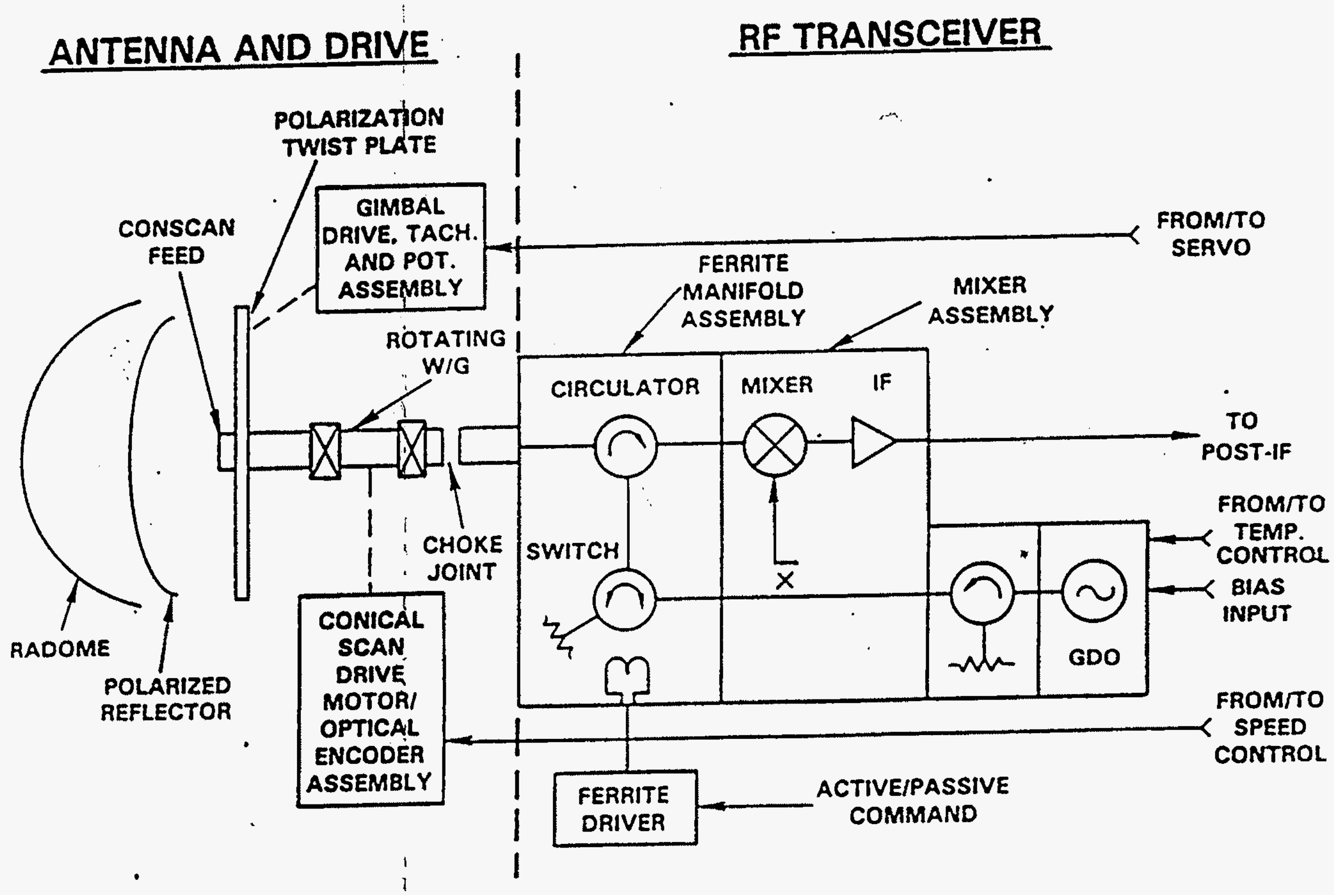

Figure 7. Manufacturing Methods and Technology Components, Millimeter Seeker Front End [72]

V. THE MONOLITHIC MILLIMETER AND MICROWAVE INITIATIVE (M^3I) COMMITTEE

In August 1984, in preparation for the DSARC on MLRS-TGW the following month, the Office of Under Secretary of Defense for Research and Engineering requested cost and technical data on the maturity of millimeter wave technology from the Advanced Sensors Directorate, MICOM. In response, the results of the MM&T project on Millimeter Wave Seekers conducted by Sperry was submitted along with the quick-look IR&D analysis and the follow-up state-of-the-art review by Deo and Toulious. A proposed DoD program on MIMIC was also submitted (Appendix C). As a result, concern was expressed in the DSARC review on 28 September 1984, about the absence of a mature technical base on which to establish the program. As a follow-up action, the Assistant Secretary of Defense for Acquisition Management asked the Product Engineering Service Office (PESO) to look into the state-of-the-art of millimeter wave components. Cornelius "Neil" Sullivan in PESO was tasked to contact the Office of Under Secretary of Defense for Research and Advanced Technology, ODUSD (R&AT), to obtain their cooperation in organizing a program in millimeter wave technology. Dr. Robert J. Heaston, Staff Specialist for Weapons Technology in ODUSD (R&AT) was selected to work with him. On 9 January 1985, Dr. Heaston prepared a cover brief for ODUSD (R&AT) to USDRE requesting the formation of a DoD committee to recommend a millimeter wave initiative. On 1 February 1985, USDRE James Wade signed the memorandum to the services and DARPA on "OSD Microwave/Millimeter Wave Monolithic Technology Initiative." [73] The M^3I Committee was thus established with R. J. Heaston and C. L. Sullivan as co-chairmen of the committee. The membership of the committee is shown in Figure 8. At the kickoff meeting held on 5 March 1985, in Rosslyn, VA, Sonny Maynard gave a presentation on "GaAs MMIC Initiative." [74] Following the meeting at Georgia Tech on 18-19 March 1989, the committee made onsite visits to 19 corporations beginning in late March 1985. [75] Nicholas Mangus and Thomas Barley served as MICOM representatives on the committee. The committee continued to request data of MICOM on the requirements of MIMIC to support the Army thrust in smart weapons. Figures 9 through 11 were part of the briefing material furnished to the committee in response to these requests. [76] The principal task of the M^3I Committee was to establish the current state of the technology (1985) as a prerequisite to formulating the outlines of a plan. Following the industry site visits the committee concluded:

1. Few millimeter monolithic devices have been made to date;
2. Gallium Arsenide is subject to variability in quality;
3. Bringing the chips from laboratory to production is a major hurdle requiring great expense and engineering effort;
4. Rapid on-wafer testing of chips has yet to be achieved;
5. Packaging of monolithic chips has received little attention;
6. There is no good measure of yields; other materials such as indium phosphide and aluminum gallium arsenide need investigation;
7. New high-speed, high-frequency devices such as High Electron Mobility Transistor (HEMT) will require extensive work.

Efforts were made during the site visits to obtain answers to a series of questions concerning each firm's level of effort, quality of the staff, Government programs, current and projected market, and categories of device technology. The Committee's assessment of the MIMIC manufacturing technology risk is shown in Figure 12. On 14 May 1985, the M^3I Committee briefed the Deputy Under Secretary of Defense for R&AT and recommended a program of over 500 million dollars that was forwarded to the Defense Resources Board by Dr. Wade. The Defense Resources Board endorsed the program, but reduced the funds to 135 million. Mr. E. D. (Sonny) Maynard, Jr., the Director of the VHSIC program, was appointed to manage the MIMIC program, and briefed the program to USDRE on 10 June 1985 [77]. The management structure recommended by the committee for the program is shown in Figure 13. The M^3I Committee made it clear in its report the primary motivation in establishing the program:

> "The initial driver for M^3I occurred in September 1984 with the Multiple Launch Rocket System – Terminally Guided Warhead DSARC, where the future success of the program was questioned because of the lack of a sufficient technical base in the area of low-cost millimeter wave integrated circuits." [75]

The gallium arsenide markets in 1984, including both digital and the analog MIMIC technology, are shown in Figure 14 with a projection of the market for 1990. The large growth projected for commercial computes has not materialized.

CO CHAIRMEN: ROBERT HEASTON, R&AT
CORNELIUS SULLIVAN, AM

ARMY

LT. COL. BRIAN RINEHARD, HQ ODCSDRA
VLADIMIR G. GELNOVATCH, ERADCOM
HANS HIESLMAIR, ERADCOM
LOTHAR WANDINGER, ERADCOM
JAMES KESPERIS, ERADCOM
NICK MANGUS, MICOM
TOM BARLEY, MICOM
HARRY WILLING, MICOM
WILLIAM RITCHIE, AMMCOM/ARDC
KEITH LYDING, AMCCOM/ARDC
NORMAN GOLDFARB, AMCCOM/ARDC

NAVY

CHAS CAPOSELL, ASW
JIM CAUFFMAN, NAVELEX
RON WADE, NAVELEX
DREW GLISTA, NAVAIR
GEORGE CUDD, NAVAIR
PETE LUPINO, NAVAIR
JOE ZELINSKI, NAVAIR
G.M. BORSUK, NRL
BARRY SPEIRMAN, NRL
KEN SLEGER
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KEITH CARTER, AFWAL/AADM
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MISOOM MAH, WPAFB, AVIONICS
MARC CALCATERA, WPAFB, AVIONICS
JOHN SCHINDLER, USAF/RADC
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FRANK WELKER, USAF/RADC
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LTC. GARY W. CHESNEY, SPACE DIVISION, AFSCF

DARPA

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GACIAC/IIT RESEARCH INST.

CHARLES SMOOTS
JOHN TEKIELA

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R. GILBERT
E. MAYNARD

AEROSPACE CORP

C.C. LEE
DONALD ROMEO

PALISADES INSTITUTE FOR RESEARCH SERVICES INC.

NATIONAL BUREAU OF STANDARDS

BRIAN BELANGER

Figure 8. DoD Monolithic Millimeter and Microwave Integrated Circuits Committee [75]

- **ARMY SMART MUNITIONS WORK IS AT 35GHz AND ABOVE**
- **THE PRINCIPAL THRUST OF MIMIC THEREFORE MUST BE AT 35GHz AND ABOVE**
- **THE TECHNOLOGY IS GENERALLY LESS MATURE AT THE HIGHER FREQUENCIES**
- **AFFORDABILITY AND PRODUCIBILITY ARE KEY DRIVERS FOR SMART MUNITIONS**
- **INDUSTRY ALLOCATES LITTLE FUNDING TO PRODUCIBILITY UNDER IR&D**
- **GENERIC CHIP SETS, COMPUTER-AIDED DESIGN TOOLS, RF SHIELDING AND PACKAGING, AND FLEXIBLE AUTOMATED PRODUCTION TESTING ARE NEEDED EFFORTS**

Figure 9. A Microwave and Millimeter Monolithic Integrated Circuit Program for Smart Munitions [76]

TWO-TERMINAL DEVICES

- CURRENT ARMY SMART MUNITIONS EFFORT IS BASED ON TWO-TERMINAL DEVICES
- TWO TERMINAL DEVICES LESS COMPATIBLE WITH MONOLITHIC PROCESSING
- THERMAL DESIGN IS A MAJOR TECHNICAL CHALLENGE, PARTICULARLY AT W-BAND
- MATERIAL PROPERTIES HAVE A STRONG INFLUENCE ON YIELD AND PERFORMANCE
- THE ONLY TECHNOLOGY AVAILABLE FOR POWER GENERATION AT W-BAND

THREE-TERMINAL DEVICES

- BASIC DEVICE FUNCTIONS HIGHLY COMPATIBLE WITH MONOLITHIC PROCESS TECHNOLOGY
- THERMAL DESIGN IS A MAJOR TECHNOLOGY CHALLENGE
- ELECTRON BEAM LITHOGRAPHY IS ESSENTIAL FOR EXTENDING TECHNOLOGY ABOVE 35 GHz
- HAS RECEIVED MORE INTENSIVE DEVELOPMENT OVER THE PAST DECADE THAN TWO-TERMINAL TECHNOLOGY

Figure 10. Circuit Functions for Millimeter Integrated Circuits [76]

- MATERIAL GROWTH AND CHARACTERIZATION MUST BE GREATLY IMPROVED AND EFFECTS OF MATERIAL PROPERTIES ON DEVICE PERFORMANCE ESTABLISHED.

- THE DEFINITION OF GENERIC CHIP SETS AND SUBSYSTEM BLOCKS THAT MEET ARMY NEEDS IN SMART MUNITIONS MUST BE MADE TO CONTROL DESIGN COST.

- DEVICE AND CIRCUIT MODELS FOR ANALYSIS AND SYNTHESIS OF MONOLITHIC CIRCUITS IN COMPUTER-AIDED DESIGN PROGRAMS MUST BE ESTABLISHED AT THE SHORTER MILLIMETER WAVELENGTHS.

- TECHNIQUES FOR ON-CHIP RF TESTING MUST BE DEVELOPED AND STANDARDS FOR MEASUREMENTS AND INSTRUMENTATION ESTABLISHED.

- A SEARCH FOR OPPORTUNITIES TO COMBINE MILLIMETER FUNCTIONS AND DIGITAL SIGNAL PROCESSING ON ONE CHIP MUST BE MADE.

- PACKAGING AND SHIELDING, A MAJOR COST ELEMENT OF THE TECHNOLOGY, NEEDS FURTHER DEVELOPMENT.

Figure 11. MIMIC Technology Challenges for Smart Munitions [76]

		2-20 GHZ-NAVE ELECT. WARFARE	22/44 GHZ-AF SATELL. COM MILSTAR	35 GHZ-ARMY SMART MUNI-TIONS/SADARM	94 GHZ-ARMY TERMINAL HOMING
TRANSMIT	POWER SOURCE	M	M	M	H
	COMBINER	L	M	M	M
	MICROSTRIP, PLANAR WAVEGUIDE	L	M	M	M
RECEIVE	LOW NOISE	M	M-H	M-H	H
	IF AMP	L	M	M	M
	MIXER	L	M	M	M
CONTROL	LIMITER	L	L	M	H
	PHASE SHIFTER	M	M	M	H
	RF SWITCH	L	L-M	L	H
ANTENNA	RADOME WINDOW	L	L	L	H
	CIRCULATOR	M	M	M	H
	MULTIPLEXER	L	M	L	M

L = 1 – 3 YEAR HORIZON
M = 3 – 5 YEAR HORIZON
H = 5 – 10 YEAR HORIZON

Figure 12. MIMIC Manufacturing Technology Risk [75]

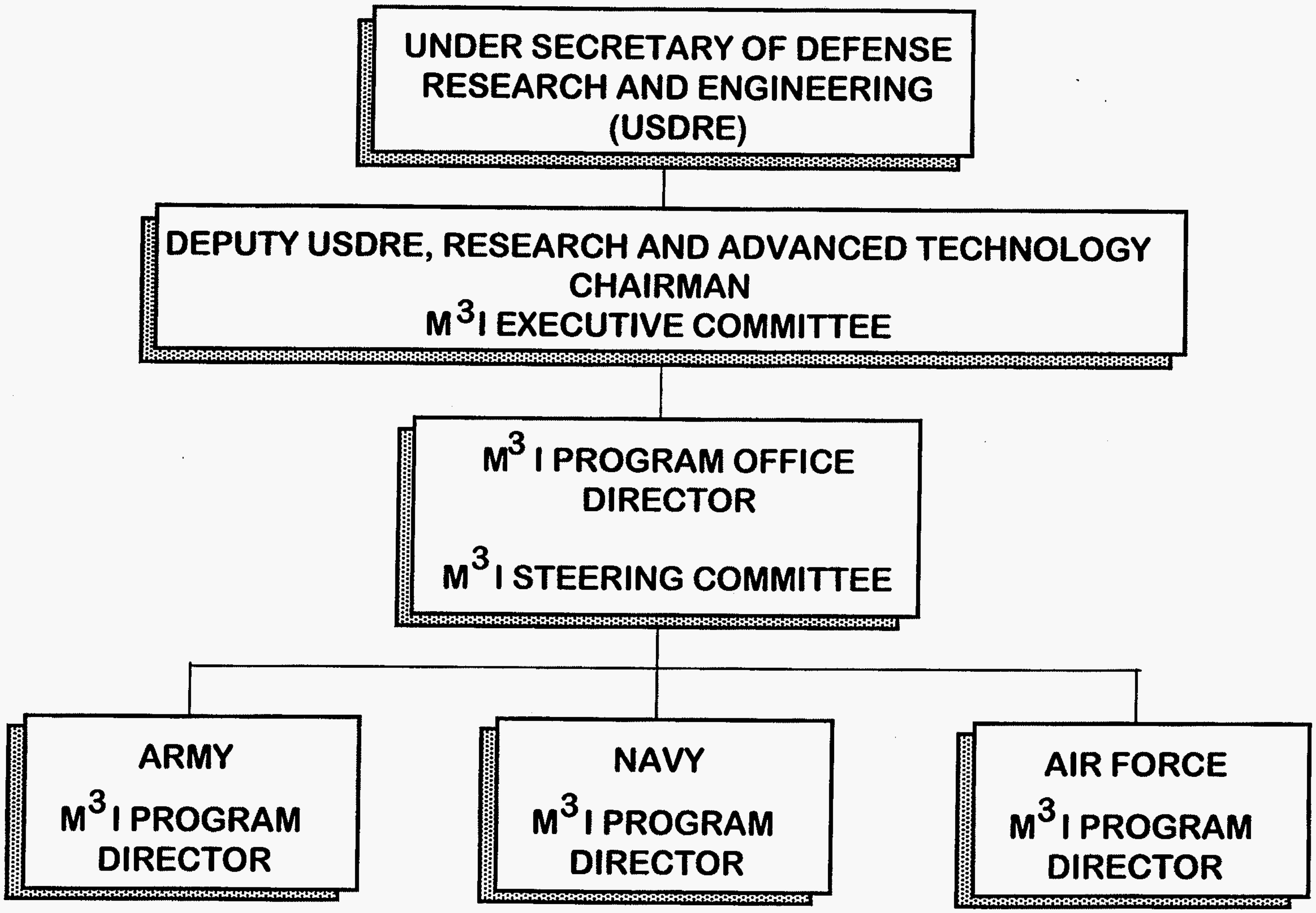

Figure 13. MIMIC Management Structure Proposed by the DoD M^{3}I Committee [75]

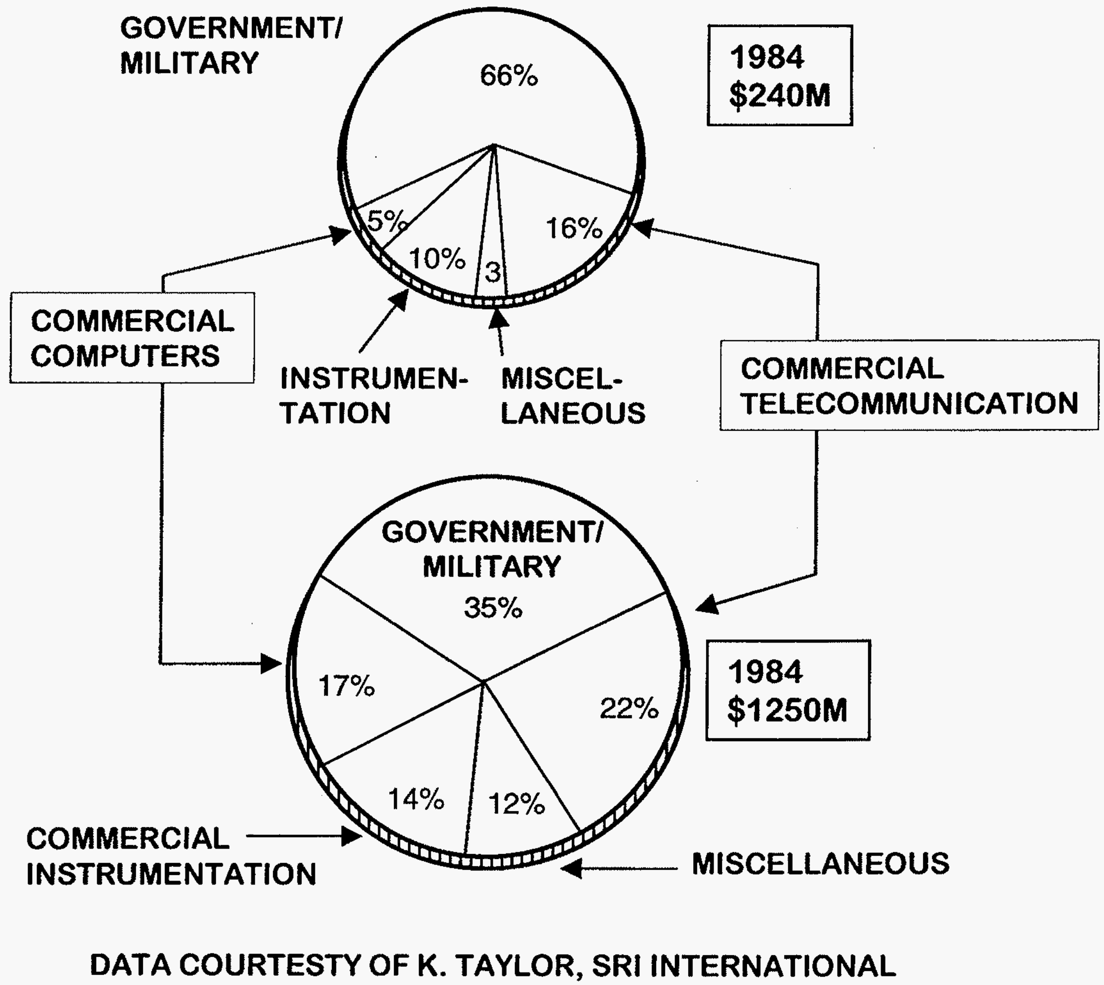

Figure 14. 1984-1990 Market Segments for GaAs Device Application [77]

VI. INDUSTRIAL BASE ANALYSIS

In the early 1980s, the outline of a national initiative began to crystallize from the numerous state-of-the-art reviews of millimeter monolithic gallium arsenide integrated circuits that appeared in both domestic and foreign publications. [78–88] The first IEEE Gallium Arsenide Monolithic Circuits Symposium was held at Lake Tahoe, NV in 1979, with 340 attending; attendance increased to 423 in 1981. The best papers from the 1981 meeting were selected for a special issue of the IEEE Transactions on Microwave Theory, July 1982, Vol. MTT-30, No. 7. The Society of Electron Devices also published Special Issues on Monolithic Microwave ICs in January 1983 (Vol. ED-30, No. 1), and December 1983 (Vol. ED-30, No. 12) with the IEEE MTT Society. In the foreword to the January 1983 issue, Gelnovatch observed that "the microwave and millimeter wave technical community stands on the doorstep of technological breakthrough [89]."Attendance at the 1983 and 1984 Symposia had increased by 40 percent per year to a number nearly double that of the 1981 meeting. By 1985, attendance had risen to 934 with an increase in attendance of 19 percent over the previous year. E. D. Maynard, Jr., announced the DoD MIMIC program at the 1985 meeting of the Government Microcircuit Application Conference, and gave the invited talk "DoD Microwave and Millimeter Wave Integrated Circuits Program" at the 1986 meeting of the GaAs Monolithic Circuits Program in Baltimore, MD on 4-5 June. He also gave the keynote talk "DoD Microwave and Millimeter Wave Program" at the Conference on Producibillity of Millimeter and Microwave Integrated Circuite, 5-6 November 1985, at Redstone Arsenal, AL. [90]

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As a small part of this activity, between 1981 and the date of the DSARC for MLRS-TGW in September 1984, MICOM put together a substantial database on millimeter integrated circuit technology. As a follow-up to the completion of the manufacturing methods and technology program by Sperry Microwave on millimeter wave seekers, an industry-wide quick look IR&D analysis was conducted in 1984 at MICOM to identify firms by name, level of effort, and the content of the research. The results showed there were 40 companies working in the field of millimeter integrated circuits (both hybrid and monolithic) with practically no work that could be classified as manufacturing process development. Only 5 firms had levels of effort well above the other 35. There were approximately 375 man-years of IR&D efforts DoD-wide. As a follow-up to this analysis, a task to conduct an industry-wide survey of the technology was also prepared at MICOM to focus on a more detailed technical analysis. This task was executed as an amendment to a solicitation issued by ITT Research Institute, 30 July 1984, by Dr. Naresh C. Deo of the Millitech Corporation and Dr. Peter Toulios of Epsilon Lamda Electronics. [91-93]

The state-of-the-art analysis performed by these authors included: (1) the characteristics of circuit functions for monolithic realization, (2) the design process for MIMIC, (3) the transmission line structures suitable for planar monolithic fabrication, and (4) the major technological issues and problems. The authors also clarified the distinction between "millimeter integrated circuits" (MICs or hybrids) and "millimeter monolithic integrated circuits" (MMICs or MIMICs). The authors concluded with a summary of the most significant accomplishments that led to the present state-of-the-art (1985) with the potential for further advances.

The first generation of millimeter wave components, circuits, and systems were derived from scaling in wavelength from the well-established microwave technology. However, this required extremely tight tolerances, bulky structures difficult to package with high losses. In between this generation of technology and the monolithic integration of both active and passive circuit elements in a single substrate, Deo and Toulios found various approaches to achieving some degree of "integration" that are characterized as "millimeter integrated circuits" or MICs (hybrids). Both technologies were initially included in developing the criteria for the MIMIC program, but subsequently, MICs or hybrids were dropped in light of the overwhelming advantages of MMICs or MIMICs in cost, size, weight, volume, and reliability.

Four transmission line structures were identified as having potential for planar monolithic integration: the microstrip line, slot line, coplanar waveguide, and coplanar stripline (Figs. 15 and 16). From the analysis Deo and Toulious concluded there was no single transmission line medium that was ideal [92]. An examination of both two-terminal and three-terminal devices (Fig. 17) for four-circuit functions, showed that conceptually both classes of devices could be applied in the four-circuit functions, but in practice, there were severe limitations. The device geometries of two-terminal devices were not readily adaptable to monolithic integration although planar fabrication of Gunn devices had been demonstrated in 1968. Deo and Toulious highlighted the potential of two three-terminal devices: the Hetrojunction Bipolar Transistor (HBT), and the HEMT that would both be featured prominently in the MIMIC program. The most serious voids in MIMICs at the time of the analysis was in the area of power generation, particularly above 35 GHz, an issue of great importance to the smart weapons community. In an examination of the design rules imposed by monolithic integration, the authors found a number of constraints that represented a departure from the design rules for hybrid integrated circuit technology, as shown in Figure 18. An assessment of the several methods of growing the bulk starting material, the manufacturing processing steps in gallium arsenide, and epitaxial methods of growth was also part of the study.

The concern of the smart weapons community at the time of the analyses was whether or not active devices from the MIMIC program could be made to provide adequate power at 94 GHz. The two-terminal active devices (Gunn diodes and IMPATTS) in addition to not being readily adaptable to monolithic processing, had other limitations, but the use of e-beam lithography in achieving gate lengths of less than .5 microns for MESFETS had been a factor in achieving operation above 35 GHz with three-terminal devices. Deo and Toulious recognized the most critical challenge was the development of new active three-terminal device structures:

> "To meet the needs of a growing millimeter wave market, however, a new generation of transistors must be developed with superior high frequency characteristics, beyond the capability of current GaAs MESFETS." [93]

At the beginning of the formulation of the MIMIC program in 1985, the Army had a total of \$2.3 million allocated for the technology in 6.1, 6.2, and MM&T; the Navy had a total of \$7.1 million also in these same categories. The Air Force had by far the largest program with a total of \$19.4 million in 6.1, 6.2, MM&T, and 6.3A. [94] The industrial base analysis of IR&D programs performed at Redstone Arsenal the prior year showed that there were approximately 40 companies working in the field, but almost no work in the area of manufacturing process development. Also, in contrast to these programs in analog technology, the Strategic Defense Initiative had \$22 million in funding for digital gallium arsenide technology to take advantage of the radiation hardness of this material for space applications. In 1985, the principal application of the digital technology was military, but the military application was projected to shrink as a fraction of the total as the growth of digital gallium arsenide grew in the commercial computer market – a projection that never materialized. The digital program was not part of MIMIC (Fig. 14).

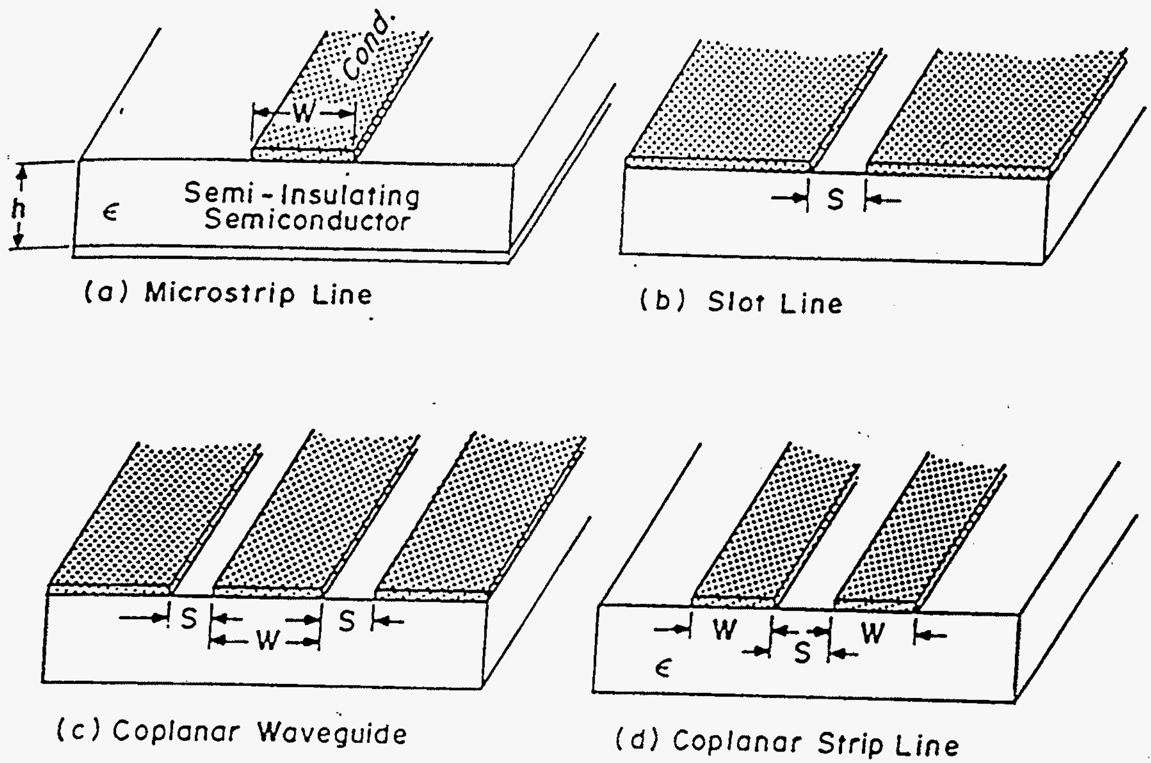


Figure 15. Transmission Line Structures for Monolithic Integrated Circuit Realization [91, 93]

	MICROSTRIP LINE	COPLANAR WAVEGUIDE	COPLANAR STRIP LINE	SLOT LINE
ATTENUATION	LOW	MEDIUM	MEDIUM	HIGH
DISPERSION	LOW	MEDIUM	MEDIUM	HIGH
IMPEDANCE RANGE,	10-100	25-125*	40-250*	HIGH
CONNECT SHUNT ELEMENTS	DIFFICULT	EASY	EASY	EASY
CONNECT SERIES ELEMENTS	EASY	EASY	EASY	DIFFICULT

* INFINITELY THICK SUBSTRATE.

Figure 16. Relative Properties of Various Transmission Lines [91, 93]

CIRCUIT FUNCTION	TWO-TERMINAL DEVICE	THREE-TERMINAL DEVICE
POWER GENERATION	TED (GUNN FAMILY), IMPATT DEVICES	MESFET, MODFET, HJBT, HEMT
AMPLIFICATION	GUNN DEVICES, DISTRIBUTED GAIN ELEMENT	MESFET, HEMT HJBT, MODFET,
MIXER/DETECTOR	SCHOTTKY BARRIER DIODE, JOSEPHSON JUNCTION DEVICE	MESFET
CONTROL FUNCTION	PIN, NIP STRUCTURE	MESFET, DUAL-GATE STRUCTURE
TUNING DEVICE	VARACTOR	FET

Figure 17. Devices for Monolithic Circuits and Their Applications [91, 93]

- Space taken by the passive elements in the circuit must be kept to a minimum
- The range of element values permitted is limited by the planar format.
- The circuit performance characteristics must be tolerant of the expected variation in device parameters due to the lack of any tuning capability to compensate for device parameter variations.
- Circuit complexity and chip partitioning are determined by yield objectives, what can and cannot be implemented monolithically, problems in biasing, and isolation requirements.

Figure 18. General Constraints Imposed on the Design Process for Monolithic Millimeter and Microwave Integrated Circuits [91, 93]

Other state-of-the-art reviews, published on the eve of the beginning of the MIMIC program, identified gaps in the technology and recommended specific courses of action for DoD. For example, A. Christou [84] identified needs in materials growth and characterization, FET process technology, lithography, ohmic contacts, Schottky gate formation, passive element processing, device modeling, and computer-aided design tools. Sleger [85] summarized the GaAs monolithic analog components manufacturing puzzle (Figs. 19 and 20) from the 1985 perspective that included 13 pieces of the puzzle, and concluded that DoD needed a strategy for success in MIMIC manufacturing and warned that if a domestic manufacturing base for MIMIC did not evolve within the next 5 years, the threat of foreign competition would be very real. In another paper, Sleger [80] presented a broad overview of applications of GaAs to Government systems, that included the results of a survey that displayed the system type versus the chip description, IC development, IC application, and potential chip buy. The Army, Navy, and Air Force were included in the survey. Sleger included both analog and digital GaAs in the analysis, and presented a funding summary for DoD and NASA in gallium arsenide monolithics, principally 6.2, for the 10-year period from 1973 to 1983 (Fig. 21).

David K. Ferry and 14 other top experts from industry, academia, and Government produced an excellent benchmark in the publication of the book <u>Gallium Arsenide Technology</u> that was published the same year the MIMIC program was announced. [95] The book included topics in the three application areas of gallium arsenide: digital, analog, and microwave photonics. The first demonstration of the HEMT device was in 1980, and the pseudomorphic HEMT was introduced the year the book was published. The authors of Chapter 4 (Tu, Hendel, and Dingle) took note of the rapid growth in papers on selectively doped hetrostructure transistors over this 5-year period. The growth of world-wide sales of molecular beam spitaxy systems over this same period grew from 13 systems in 1980, to 86 systems in 1986. [95] Clearly, David K. Ferry's optimistic observation in the Preface was well-founded:

> "Gallium Arsenide is the material of the future. This statement has been the logo for workers in the Field for over thirty years now. One may readily ask whether or not we will ever see large scale usage of gallium arsenide circuits. There have been long and bitter discussions between its advocates and is antagonists, yet, I feel that we can reasonably answer in the affirmative."

But, a later statement that "GaAs is today (1985) a firmly established technology" is a bit too strong. It would take the 7-year MIMIC program to make this true for analog gallium arsenide technology. In 1986, Gelnovatch called for a "Microwave VHSIC Program." [96]

PUZZLE PIECES	1985 STATUS
Semi-Insulating substrate quality and availability	-- Available in pilot line quantity -- 3" wafers need flatness improvements -- Dislocation density may require improvement. -- Industry depends on foreign sources
Processing Equipment (Focus on 0.5 to 1.0 micron definition over long gate width runs)	-- Mostly available from silicon industry -- Could require special equipment for short run innovative manufacturing -- E-beam not high volume oriented -- Processing still in evolutionary stage
Device and Circuit Models (1-100 GHz)	-- Formidable for active devices -- Large signal models limited -- Limited accuracy above 10 GHz -- In development above 20 GHz -- No general techniques for circuit design
Process Models	-- Limited for silicon -- Emerging for GaAs - no standard process
Computer Aided Design (1-100 GHz)	-- Limited to COMPACE, SPICE, CADEC -- Non-linear circuit design non-existent -- Limited microwave circuit elements -- Iterative procedure takes months (cost barrier) -- Unavailable above 20 GHz -- Considered a research frontier for MMIC
Computer Aided Engineering and Manufacturing (1-100 GHz)	-- Embrionic to non-existent -- Analog (RF) compiler may become available in 1985
Custom Design (1-100 Ghz)	-- Many (in response to DOD funding) Yields below 1% on 2" wafers Very high performance -- Cost barrier
Standard Designs (1-100 GHz)	-- Commercially driven - low cost -- Many use distributed amplifier concepts -- Most foreign activity here -- Cost and performance Impact for DOD?

Figure 19. GaAs Monolithic Component Manufacturing Puzzle: 1985 Perspective [85]

PUZZLE PIECES	1985 STATUS
Second Generation Technologies (Example: MODFET)	-- Research and development -- MODFET a candidate for generic low noise amplifier -- Market niche not determined
Short Run Concepts for Volume Generation	-- Being developed for silicon -- Ready by 1988? -- A key to affordability for GaAs
Human Resources	-- Business perception; Increased DOD funding in FY '86 to FY '90 may be counter productive to manufacturing
Packaging	-- Limited to narrowband designs -- Unavailable for wideband designs in off-the-shelf quantity -- In development above 20 GHz--critical cost barrier
Assembly	-- Limited to MIC experience -- Undeveloped for MMICs with 4 millimeter substrates -- Critical cost barrier
DC and RF Testing	-- Available: 2-18GHz wafer/package -- Limited: Above 20 GHz -- Cost barrier
Quality Outlook	-- Transition to quality outlook beginning in DOD pilot lines and component houses
Business Outlook	-- Technologist driven -- systems cost savings unknown -- Components required for DOD systems pull -- Strong commercial market emerging with questionable impact on DOD needs
Reliability, Radiation Tolerance Operation in Harsh Environments	-- Reliability, radiation tolerance data very limited -- Design for reliability, radiation tolerance non-existent -- Operation over military temperature range not demonstrated

Figure 20. GaAs Monolithic Component Manufacturing Puzzle: 1985 Perspective [85]

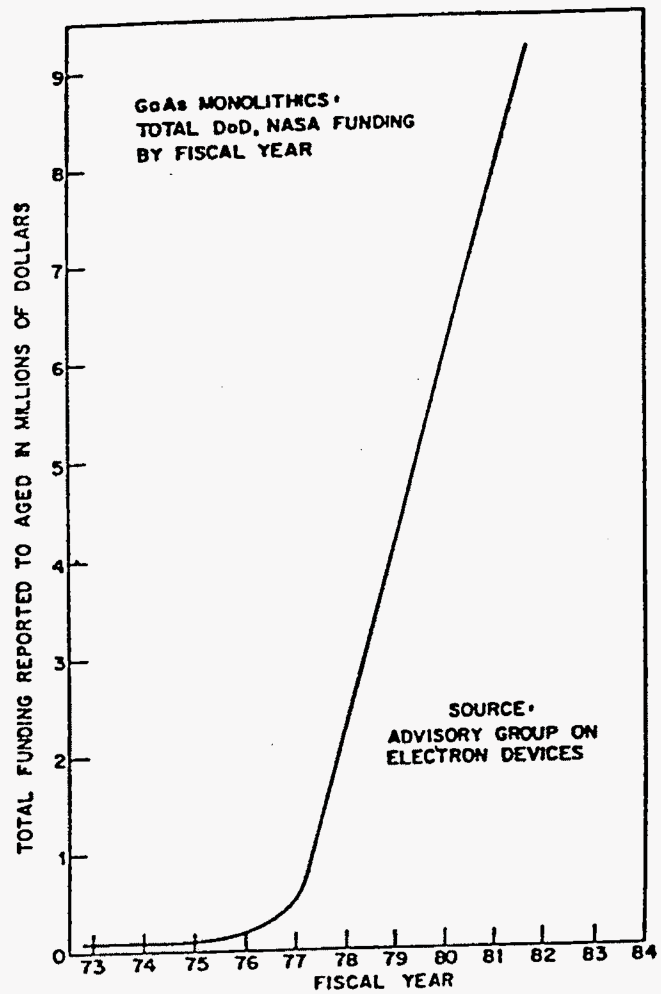


Figure 21. DoD, NASA Investment in GaAs Monolithics Component Principally 6.2 Exploratory [85]

The 84 carefully selected seminal papers in the 1985 IEEE book Monolithic Microwave Integrated Circuits seemed to provide the framework for the DoD MIMIC program announced by E.D. Maynard that year. [97] The potential benefits and limitations of both the monolithic and hybrid technology had been explored, and new directions for research were defined to overcome the limitations in the monolithic technology. The key cost drivers in each step of the gallium arsenide process from starting material to finished chip had been identified, thus providing the focus for much of the work executed under the MIMIC program. The growing patent literature in MESFETS the year the book was published underscored the importance of the MESFET as the key active device in MIMIC technology. Both civilian and military applications were foreseen (direct broadcast receivers, and phased array radars), and work was in progress on MIMIC devices in the 94 Ghz region of great interest to the smart weapons community. The progress in CAD for HMICs had established the springboard for CAD for MIMIC, and new test, measurement and diagnostic techniques were emerging to meet the challenge for MIMIC. Clearly, the scope of the effort identified in the 84 seminal papers was beyond the capability of individual organizations. It was up to DoD to serve as catalyst in releasing the creative energies in a focused effort to achieve national objectives.

The vigorous activity in MIMIC during the course of Phase I was reflected in the publication of Monolithic Microwave Integrated Circuits in 1989 that spanned the process from beginning to end in a format suitable for a two-semester college course as well as the practicing engineer. [98]

VII. THE NEED FOR A STRUCTURED PROGRAM

As noted, it was the MLRS-TGW program that drove the decision by the Under Secretary of Defense for Research and Engineering to establish the structured MIMIC initiative, and MICOM provided part of the supporting data leading to that decision. The first effort to highlight the need for such an initiative was made when the SPIE Conference on Integrated Optics and Millimeter and Microwave Integrated Circuits was organized and held on 16-19 November 1981, in the Von Braun Civic Center, Huntsville, AL. [99] Potential applications of the technology had been identified and individual MM&T plans had been prepared and submitted; however, the realization grew that the technology could not be advanced through a collection of uncoordinated MM&T projects. Major investments were required that were beyond the capabilities of individual companies, and a program structure was required that would allow the application of concurrent engineering. The DoD had initiated the Very High Speed Integrated Circuit (VHSIC) program a little over a year before in March 1980, so there was little enthusiasm for another major initiative at the time. Also, MIMIC was viewed as a specialized niche technology that did not deserve the same level of attention as a broad generic technology such as VHSIC; MIMIC was too much in the shadow of VHSIC at the time. However, one of the conclusions of the conference was that MIMIC was mature enough to sustain a structured program, but integrated optics was not.

Several events converged to create a climate favorable to the formulation of a national program in monolithic millimeter and microwave gallium arsenide technology. As noted, all three services, DARPA, and the Strategic Defense Initiative Organization, had analog millimeter wave monolithic gallium arsenide programs as part of programs in millimeter wave technology, but it was the perception in Congress that these were uncoordinated. As a result, the services were asked to explain the duplication in the technology. (The result of this examination at Redstone Arsenal was that the 1498s were, in many cases, unfunded, or the term "millimeter wave" was misused in the title as a catchy phrase for use in budget documents.) In addition, the Committee on Critical Materials after reviewing MM&T projects completed and planned at MICOM on 9 December 1985, observed in their report:

> "The combined effort that exists in the United States, including that in the Army and other military organizations, industry and universities is not sufficient to present the ultimate dominance by the Japanese as suppliers of III-V compounds, materials, devices, and circuits." [100]

Also, the data emerging from the MM&T programs was leading to the inevitable conclusion that achieving competitiveness on a national level could not be achieved through the summation of uncoordinated individual projects in 6.1, 6.2, MMT. For example, in the MM&T study on the Assault Breaker Drop Test Millimeter Seeker discussed earlier, Sperry concluded that in the 1983-84 period, it would be possible to achieve a "fully integrated" RF front end production cost of 2,300 dollars at a production rate of 800 per month for a total of 50,000 units; but to achieve a monolithic front-end for a cost of 900 dollars would require an expenditure of 8 to 10 million over a 5- to 8-year period. Clearly, this estimate for one firm and one project was far below the investment needed to achieve competitiveness on a national level. [71, 72]

(Incidentally, the term "fully integrated" in the report does not mean monolithic, but refers to "millimeter integrated circuits", or MICs, meaning hybrids.)

Clearly, a structured program was needed to achieve some economy of scale in the research and development process, as well as the manufacturing process development, and a model for accomplishing this was provided by the VHSIC. The MIMIC team approach brought together the systems houses, foundries, specialty firms skilled in software tool development, device physics, modeling and simulation, on-chip testing, and others. As a follow-up to the paper presented at the SPIE Conference on Integrated Optics and Millimeter and Microwave Integrated Circuits, 16-19 November 1981 (SPIE Volume 317), an Army-wide proposal, "A Structured Program in Microwave and Millimeter Circuit Technology" (Appendix B), was prepared and submitted to the Army which reflected this structured approach. [101] Also, a revised version for DoD: "Improving the Availability, Affordability and Producibility of Microwave and Millimeter Integrated Circuit Technology" (Appendix C) was submitted to DDR&E in August 1984, in response to a request from the USDRE. [102]

The need for a structured program was clearly delineated in the planning directives and memoranda issued by DDR&E. For example, the memorandum prepared by Dr. Robert Heaston and signed by James Wade on 1 February 1985, to the Assistant Secretaries of the military departments and DARPA contained the following:

> "It is generally agreed that no single guidance and control, electronic warfare, communications, or radar program can afford to adequately advance the technology that needs to be supported. Too many gaps remain unfunded if we continue to support a series of disconnected individual programs. Consequently, critical technology needs, generic chip designs, required testing capabilities, and mass production techniques need to be identified and funded as a coordinated DoD-wide program." [103]

In Criteria for DoD Program in Microwave and Millimeter Integrated Circuits, dated 19 March 1985, is the following:

> "The program should not just be "more of the same" of what industry is doing under the IR&D program, but provide the basis for the Government to be a smart buyer of the technology as well as strengthening the industry itself." [104]

The criteria also made producibility goals rather than performance goals the major thrust of the program, and provided a strong role for the DoD in-house laboratories. Both hybrid and monolithic technologies were to be included in the program according to the criteria, but hybrid technology was subsequently dropped.

VIII. 1985-1986 MIMIC PLANNING CONFERENCES, HIGHLIGHTS, CHALLENGES

The U.S. Army Technology and Devices Laboratory served as host for the U.S. Army Gallium Arsenide Workshop on 24 through 26 February, which included: (1) Industry Capability Baseline Review, (2) TRADOC Requirements, (3) Army System Managers Requirements (1990-2010), and (4) SDI/DARPA Inputs. Also, on the agenda were workshops by the four key specialty areas: Smart Weapons, Electronic Warfare, Radar, and Communications. [105]

Potential programs to meet service requirements was the theme of the workshop held on 18-19 March 1985, by the M31 Committee at Georgia Tech Research Institute with participants from the three services. [106] As a follow-up to the earlier industrial base analyses, members of the Committee visited 19 corporations heavily involved in MIMIC technology. A summary of the results of these visits is contained in Reference 107.

On 5-6 November 1985, the Missile Research, Development, and Engineering Center served as host for the 1985 Producibility of Microwave and Millimeter Wave Integrated Circuits Conference. [108] Dr. E.D. (Sonny) Maynard, Director of the VHSIC Program office and the MIMIC Program Office gave an outline of the structure of the MIMIC program and observed that the MIMIC program would provide the "eyes and ears" of systems that have "brains" provided by VHSIC, with similar benefits provided by both technologies. The program structure of MIMIC according to Maynard would be similar to that of VHSIC. The conference program included seven sessions: (1) Overview, (2) Materials, (3) Reliability Physics and Environmental Effects, (4) Production Testing, (5) Process Technology, (6) Applications, and (7) Roundtable Discussion. The Overview session included "DoD Needs for Measurement Standards," and "State of the Art Review of Microwave and Millimeter Wave Monolithic Integrated Circuits" and an "Overview of the AMC Smart Munitions Center."

A key theme of this conference was the wide gap between the growth of the microwave and millimeter wave industry and declining funding for the NBS to develop the metrology to support the industry. In 1984, the IEEE MTT-S Society of Microwave Theory and Techniques formed the Committee to Promote National Measurements Standards (PNMS). The PNMS Committee conducted a detailed study of NBS and several other national measurement laboratories with the help of the International Scientific Radio Union (URSI). The conclusion was the NBS had lost its world leadership position. Plans began immediately after the conclusion of the conference to put together a program for a two-day conference on measurement standards for miniaturized systems the following year to highlight this problem in the same week as the second Conference on the Producibility of Millimeter and Microwave Integrated Circuits. [109] On 29 January 1986, a meeting of the DoD Calibration Coordination Group (CCG), the NBS, and the DoD Laboratories was held at Redstone Arsenal to plan the agenda for the conference in 1986.

The follow-up to the 1985 conference on Producibility of Millimeter and Microwave Integrated Circuits was held on 4-5 November 1986, at the Redstone Arsenal Post Theater [109], and on 6-7 November the Conference on Millimeter and Microwave Measurement Standards for Miniaturized Systems was held in the same location. [110] The latter meeting provided a leadership role for the NBS (to become later the National Institute of Standards and Technology) in the MIMIC program that was a major factor in the success of MIMIC.

IX. MIMIC ADVANCES SMART MUNITIONS

The Multi-Option Fuze for Artillery (MOFA), the Search and Destroy Armor (SADARM), and Multiple Launch Rocket System-Terminally Guided Warhead (MLRS-TGW) were all relatively small-diameter munitions with potential for production in large numbers, and therefore attractive candidates for MIMIC insertion. The first use of proximity fuzes in combat was in World War II, and the principal change in the technology following World War II was the replacement of miniature vacuum tubes with transistors. The undesirable proximity patterns for these fuzes that operated below the microwave band required a new design for each munition. Hittite Microwave was a member of the Raytheon-Texas Instruments MIMIC team that successfully integrated all the microwave functions required by MOFA on a single chip that included a voltage controlled oscillator, amplifier, circulator, and mixer. Although no hardware was required in phase I, Hittite provided transceivers for evaluation by Armaments Research, Development, and Engineering Center (ARDEC) in prototype fuzes. Hittite delivered transceivers to ARDEC for use in 60 fuzes designed and fabricated in-house as part of the 6.3A MOFA program. Hittite was not funded in Phase II MIMIC, but continued to work to reduce the unit production lost when PM Crusader decided to fund the Phase II effort. Hittite continued to work under a contract modification to the existing Raytheon/Texas Instruments BAA. Hittite fabricated, packaged, and tested over 7500 transceivers to verify yield and performance, and demonstrated that the $10.00 cost goal could be met. [111]

The MIMIC technology offered the potential for higher precision in a transceiver at microwave frequencies and programmability that could provide detonation signals for a variety of options including contact burst, delayed burst, or proximity burst, at heights that could be varied over a wide range. The research trail that led to MOFA began in basic research in 1968-1970, and moved through all phases of acquisition to production as XM 773 MOFA. MIMIC was coupled to MOFA from the beginning of Phase 0, and in February 1995, a panel of academic and industrial leaders declared the MIMIC MOFA to be a world-class design. [112]

The SADARM is the first indirect fire, fire-and-forget munition capable of attacking enemy armor columns. The munition is configured for launching as an artillery payload with growth potential for transportation by a carrier rocket to the target area. After arriving in the target area, a parachute unfolds from the submunition and slows the descent of the submunition into the target area. During descent, a dual-mode infrared-millimeter sensor executes a circular scan. Upon detection, the error signals generated by the circular scan provide the commands for submunition to move in the direction of the target for impact. The sensor system features an infrared sensor capable of producing a full image of the target, and both active and passive sensing in the millimeter region.

The millimeter wave technology in the early generation of SADARM featured hybrid technology. MIMIC technology was identified as a technology that could improve performance and reduce size and cost. The original goal of putting all the functions of the millimeter wave transceiver on one chip was not achieved. An early perception was that higher frequency operation could improve aimpoint selection, countermeasures immunity, and receiver function to provide an extended range and a larger footprint, but this was not adopted.

The concept has been proven in over 130,000 tests, including both captive and live fire tests. The SADARM has been in production in small quantities, and the team at Picatinny Arsenal, Dover, NJ, has initiated a Product Improvement Program and a Cost Reduction Plan. [113]

The MLRS-TGW program was originally sponsored by the U.S., the United Kingdom, France, and Germany through a joint venture contractor MDTT, Inc, composed of Martin Marietta (U.S.), Diehl Gmbh (Germany), Thomson-CSF (France), and Thorn-EMI (United Kingdom). The objective of the program was to provide an indirect fire, fire-and-forget, all-weather precision guided submunition against armor that featured a millimeter wave seeker to detect, lock-on, track, and guide the warhead into the target. The baseline transceiver for the millimeter seeker consisted of two subassemblies; the transmitter developed by TRW and the receiver developed by Thomson-CSF, who was also responsible for integrating the subassemblies. The millimeter wave seeker was identified as one of the potential risk factors in the Concept Demonstration Phase, but it was concluded that the component risk was at an acceptable level to allow the program to enter the System Demonstration Phase in 1989. The plans for this part of the program provided for 44 TGSMs to be fabricated for a series of tests that included end-to-end delivery of the submunitions to the target area by the MLRS rocket, as well as drop tests of the submunition from high-speed aircraft against an array of targets. In 1990, the TGSM was down-selected as a contender for the Deep Battle mission. [114]

Among the problem areas that made the millimeter wave seeker a risk factor were: (1) The metal waveguide structure made packaging difficult; (2) High peak power was required to overcome the high circuit losses at high millimeter wave frequencies; and (3) Poor frequency stability was the result of open-loop stabilization. MIMIC offered a solution to these three problems through (1) the integration of many functions on a few chips to reduce size, (2) the use of a monolithic direct frequency synthesizer to improve stability, and (3) the use of a low-noise HEMT amplifier to reduce the noise figure of the receiver, and thus reducing the IMPATT transmitter power requirements. However, the MIMIC program was not part of the international program. The coupling of MIMIC with MLRS-TGW was accomplished outside the framework of the international program through a MICOM Manufacturing Technology (MANTECH) program initiated during the System Demonstration Phase. The Manufacturing Technology Division, MICOM, developed the insertion strategy and managed the program that achieved a number of major milestones in MIMIC technology.

The MANTECH transceiver developed by TRW met or exceeded the MLRS-TGW specifications, including (1) The first W-band power amplifier to replace the Gunn diode assembly, and (2) The first low-noise amplifier at W-band. Although the U.S. withdrew from the international program in 1992, the excellent results with the MANTECH transceiver has led to the decision by the Army to integrate it into some of the residual hardware from the international program. [115]

Since the original three smart munitions candidates were selected for MIMIC insertion, other candidates have emerged: AMRAM, PATRIOT, LONGBOW, and the BAT P31 program. The latter system will be able to capitalize on the advancements made in MIMIC transceiver technology since the MLRS-TGW MIMIC transceiver was developed. The MIMIC program

provided the stimulus for several follow-on MANTECH programs that will be reviewed in a separate publication [115].

X. THE GLOBAL ENVIRONMENT

A. Introduction

The MIMIC program was undertaken at a time when there were serious concerns about the erosion of U.S. leadership in technology. The globalization of the Defense industrial base had led to a major dependence on foreign sources for materials and components for defense. In the civilian sector, by 1984 major industries and products including automobiles and color television sets had lost 50 percent or more of their market since 1960, as shown in Figure 22. According to A. Blanton Godfrey and Peter J. Kolesar:

> "The broad picture of the sudden decline in international competitiveness of U.S. manufacturing is no less startling: a 1986 overall trade deficit of $170 billion, $59 billion of that with Japan alone, with $30 billion in that most American of industries - - automobiles. And that $30 billion is with "voluntary" export restrictions by the Japanese." [116]

In 1982, the Microelectronics and Computer Technology Corporation was formed in response to the Japanese Fifth Generation Computer Project. To strengthen U.S. Competitiveness in the semiconductor industry, Congress passed the Chip Protection Act of 1984, and the National Cooperative Research Act of 1984, to modify antitrust restrictions and provide a less threatening framework for forming joint ventures, and as a result, the Semiconductor Manufacturing Technology (SEMATECH) consortium was formed in 1987 by 14 leading major semiconductor manufacturing companies. [117] To explore the opportunities for improving U.S. competitiveness by shortening the product development cycle, DARPA conducted a Workshop on Concurrent Engineering in 1987, and the following year DARPA launched a Government-Industry-Academia consortium on concurrent engineering. The same year, the 1988 Omnibus Trade and Competitiveness Act transformed the NBS into the National Institute of Standards and Technology (NIST) with new responsibilities. Under the legislation, NIST was charged with the responsibility to transfer advanced manufacturing technology developed at NIST to industry through regional extension centers. [118] The following year, NIST served as host for the first annual MIMIC Conference at Gaithersburg, Maryland; a timely move since the MIMIC program provided a major challenge in manufacturing technology. The legislation also provided $100 million per year for five years to the SEMATECH consortium.

AUTOMOBILES	FOOD PROCESSORS
CAMERAS	MICROWAVE OVENS
STEREO EQUIPMENT	ATHLETIC EQUIPMENT
MEDICAL EQUIPMENT	COMPUTER CHIPS
COLOR TELEVISION SETS	INDUSTRIAL ROBOTS
HAND TOOLS	ELECTRON MICROSCOPES
RADIAL TIRES	MACHINE TOOLS
ELECTRIC MOTORS	OPTICAL

Figure 22. American Industries Named Products that Lost 50 Percent or More of Their Share of World Markets Between 1960 and 1984 [116]

B. U.S. Participation in an International Missile Program

It was an international program in which the U.S. was a participant that focused attention on the affordability of millimeter wave seekers and the potential of MIMIC as a solution. In 1983, the multinational MLRS-TGW program was established under a Memorandum Of Agreement (MOA) signed by the U.S., France, Germany, and the United Kingdom. A Joint Venture was formed with four national contractors: Martin Marietta Corporation (U.S.), Diehl GmbH (Germany), Thompson CSF (France) and THORN EMI, Ltd, (United Kingdom), and the internationally staffed MDTT, Inc. that performed the management function. The project management office for the program was located at Redstone Arsenal, Alabama.

As the MIMIC program approached the end of Phase I, the DoD evaluated the MLRS-TGW and two other target-sensing submunitions in response to direction by Congress, and the submunition for MLRS was eliminated in favor of an alternative selected in 1991. However, U.S. participation in the program continued under reprogrammed DoD funds approved by Congress in addition to 1992 appropriated funds to complete the development phase then in progress. In April 1992, the U.S. General Accounting Office (GAO) reported on a review of the provisions of the MOU to determine how U.S. interests were protected (Fig. 23 and 24). [119]

The GAO found that the U.S. had the highest cost share, but the lower quality work share. In addition, GAO concluded MOU provisions on data rights and termination could prove costly, and third country transfer provisions might not adequately protect U.S. interest. The GAO interpretation of the MOU was that if a country introduced a new technology during the development phase of the TGW, this could require the release of the technology to the other partner nations, and a key technology developed under a separate program affected by this interpretation was the MIMIC Program. The DoD nonconcurred with the conclusion that third country transfer provision would not adequately protect U.S. interests. The DoD also nonconcurred with the conclusion that design and manufacturing technology would have to be transferred to the other partner nations if MIMIC was introduced in the program. [106]

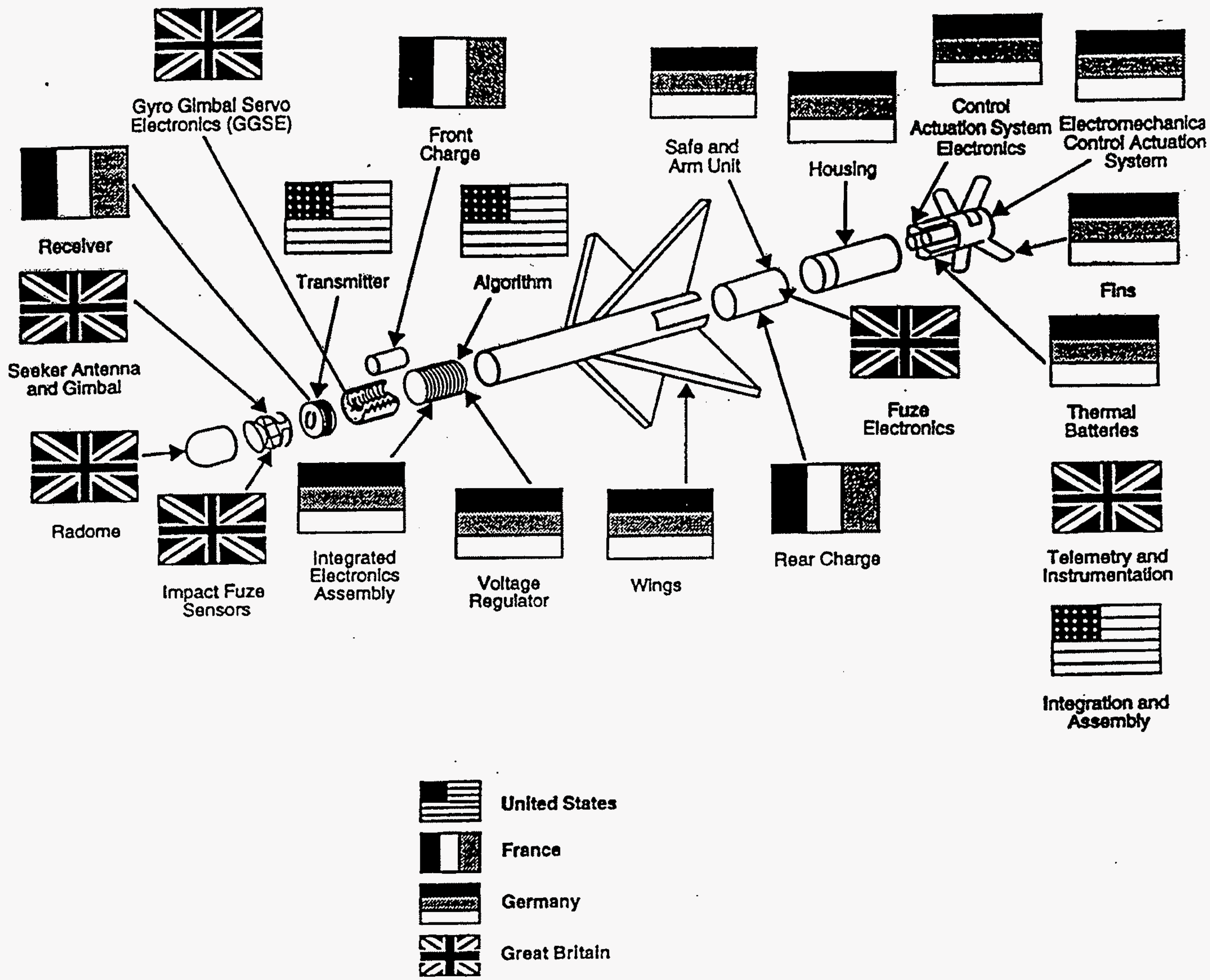


Figure 23. MLRS Terminally Guided Submunition [119]

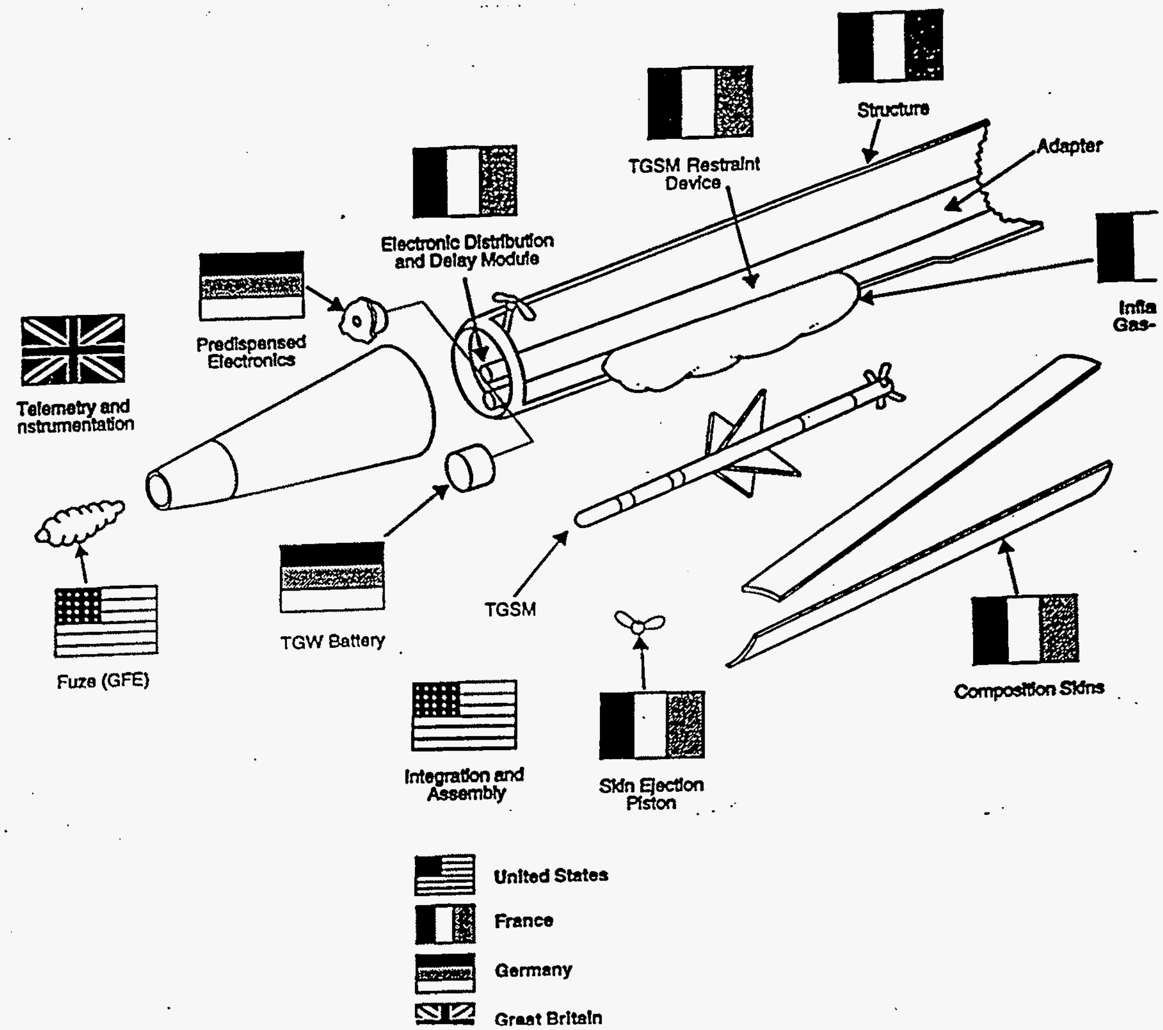


Figure 24. MLRS Terminally Guided Warhead [119]

C. Export Control Issues for VHSIC and MIMIC

During the course of the VHSIC program, the Defense Science Board Task Force devoted extensive thought to the issue of balancing the requirement for national security against the need to allow open communication among researchers in VHSIC technology to permit advancements to take place outside the arena of military weapons. Three possible control mechanisms were examined in relationship to the technology: (1) The DoD Security Classification Systems, (2) The Arms Export Control Act, and (3) The Export Administration Act. Military unique brassboard, software, and integrated circuits properly belonged under the DoD security classification guidelines. However, the dual-use nature of some of the technology having substantial application outside military systems suggested classifying it according to technology that could be inferred from finished products, and technology that could not be inferred from finished products. For the first category, the Export Administration Act was considered the appropriate control, but the second category, along with keystone fabrication equipment, design and test generation software, and remote design services were recommended for interim control under the Arms Export Control Act (International Traffic in Arms) until the Export Administration Act could be upgraded. [120]

D. Relations with JAPAN

In 1987, as the MIMIC program was getting underway, the Office of Japan Affairs was established by the National Research Council to develop improved working relationships between the scientific and technical communities of the two countries and to achieve a better understanding of Japanese science and technology.

In one study, the committee on Japan identified 12 types of U.S.-Japan alliances that could be grouped under four headings: (1) Research and Development, (2) Product Development, (3) Manufacturing, and (4) Sales and Development. For the 30 years between 1950 and 1980, the committee found that the number of alliances were few in number and restricted to the category of research and development in the form of licensing agreements for the sale of U.S. Patents to Japan. With the removal of legal and regulatory constraints, the number of alliances increased markedly as the MIMIC program was being formulated. By the time the MIMIC program was under way, a number of agreements were signed in the area of semiconductor equipment, but the number of agreements peaked before Phase I MIMIC was completed. A conclusion of the study of US-Japan strategic alliances in the semiconductor industry by the committee on Japan was that the flow of technology was one way from the U.S. to Japan. [121]

E. Defense Science Board Studies

The 1987 Defense Science Board Task Force on Semiconductor Dependency concluded that it was difficult to determine the extent that U.S. defense systems were dependent on foreign semiconductors, but the evidence indicated that for the newest systems about to be deployed, up to several tens of percent were either entirely made, or packaged and tested abroad. The Task Force found that the leadership in commercial volume production was being lost by the U.S. semiconductor industry, and the movement of manufacturing off-shore tends to pull the

"upstream" industries that support the manufacturing base along with it. The Task Force was clearly alarmed that the trend would ultimately undermine the U.S. leadership in such "downstream" industries such as computers and telecommunications that depend on a healthy semiconductor industry. The conclusion was that although the Defense Department was a customer for only a few percent of the semiconductor market, DoD was strongly dependent on a healthy semiconductor industry, and that health was maintained by high-volume commercial production. The logic of the Task Force's thought process regarding the threat is summarized in Figure 25. The threat was particularly alarming for gallium arsenide technologies for which the commercial market was limited and the Defense Department was the principal customer:

> "In nonsilicon products, such as compound semiconductor optoelectronics and fast digital technologies and particularly in optoelectronic circuits, the U.S. also trails Japan. The US currently maintains a lead in linear compound semiconductor IC technology, largely because of military interest in fast and radiation-hard circuits for satellite and radar applications." [122]

This appears to refer to the DARPA digital gallium arsenide efforts that were not part of the MIMIC program. Any lead the U.S. might have had here was of small comfort since the Task Force had concluded that the health of the semiconductor industry was dependent on high-volume commercial markets - - not small-volume defense markets which was the condition at the time of the Defense Science Board study. Much of the processing equipment for manufacturing could be applied to either silicon or compound semiconductor production, but Japan was making larger investments in the development of semiconductor manufacturing equipment than the U.S. The status and trends of semiconductor technology in Japan and the U.S. is shown in Figure 26 and trends in manufacturing productivity in the U.S., Japan, and West Germany is given in Figure 27.

In the 1988 Defense Science Board Summer Study on The Defense Industrial and Technology Base, the Board found that "If our nation is to ensure its security for the coming decade and beyond, it must adopt a strategy which links military strategy with a policy to ensure the availability of the industrial and technological resources on which operational plans rely." [123] The Board was clearly concerned that the loss of leadership in semiconductors would ultimately lead to a loss of leadership in computers.

The Defense Science Board was also asked to take a "quick relook" at the 1986 summer study on Use of Commercial Components in Military Equipment. The Board stated in their 1989 report that although there was overwhelming support for the idea, there had been little increase in the use of commercial parts in military equipment. The Board felt impelled to offer a specific course of action embodied in four thrusts: (1) a component demonstration program using microcircuits as case studies, (2) a subsystem demonstration program using computers, both hardware and software as case studies, (3) a pilot acquisition system demonstration program, and (4) establishment of new organizations to support the shift to commercial goods and practices. [124]

THE PERCEIVED THREAT TO U.S. LEADERSHIP BY THE DEFENSE SCIENCE BOARD TASK FORCE ON SEMICONDUCTOR DEPENDENCY [12]

- U.S. MILITARY FORCED DEPEND HEAVILY ON TECHNICAL SUPERIORITY TO WIN.
- ELECTRONICS IS THE TECHNOLOGY THAT CAN BE LEVERAGED MOST HIGHLY.
- SEMICONDUCTORS ARE THE KEY TO LEADERSHIP IN ELECTRONICS.
- COMPETITIVE, HIGH-VOLUME PRODUCTION IS THE KEY TO LEADERSHIP IN SEMICONDUCTORS.
- HIGH-VOLUME PRODUCTION IS SUPPORTED BY THE COMMERCIAL MARKET.

Figure 25. The Perceived Threat to US Leadership by the Defense Science Board Task Force on Semiconductor Dependency [122]

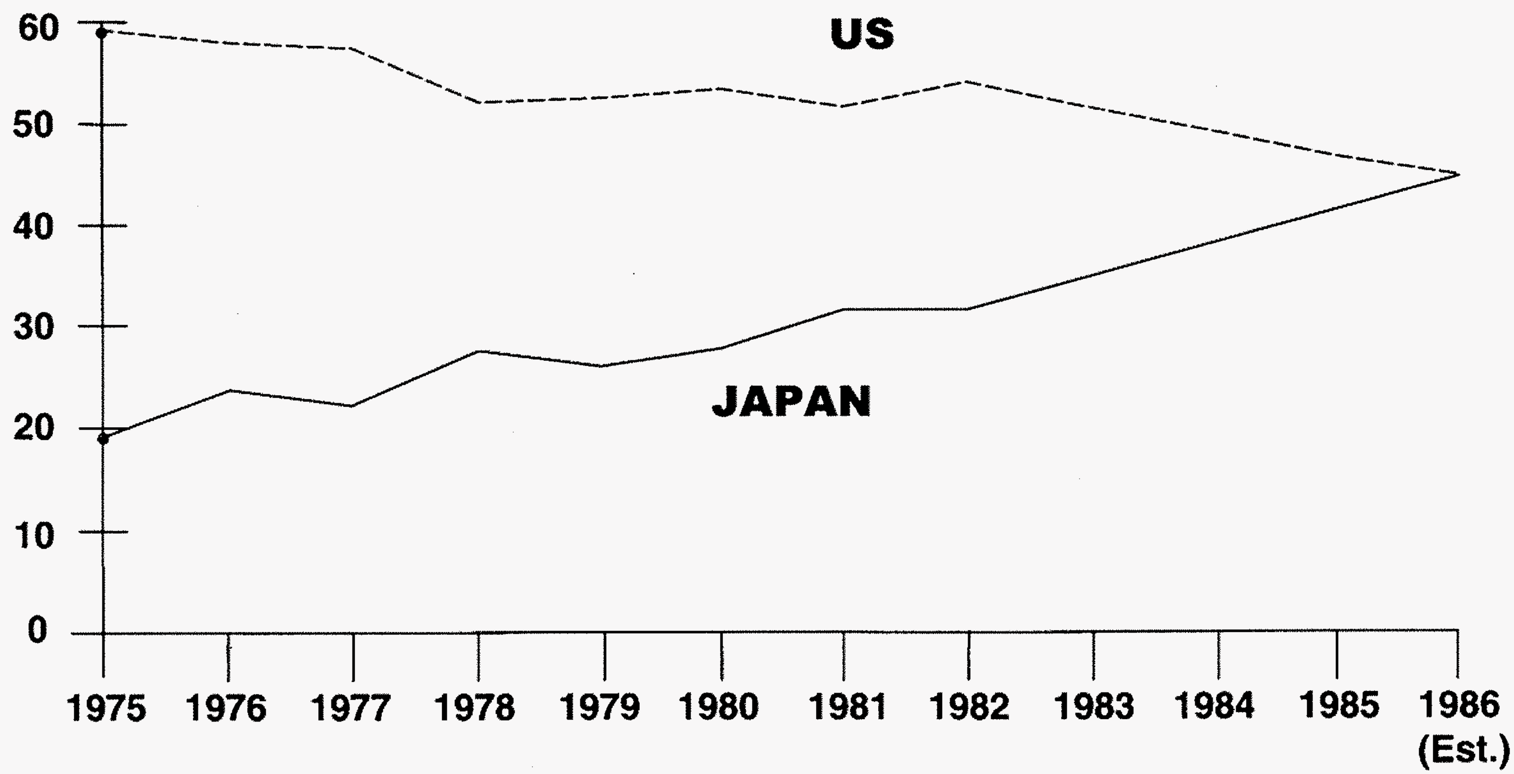
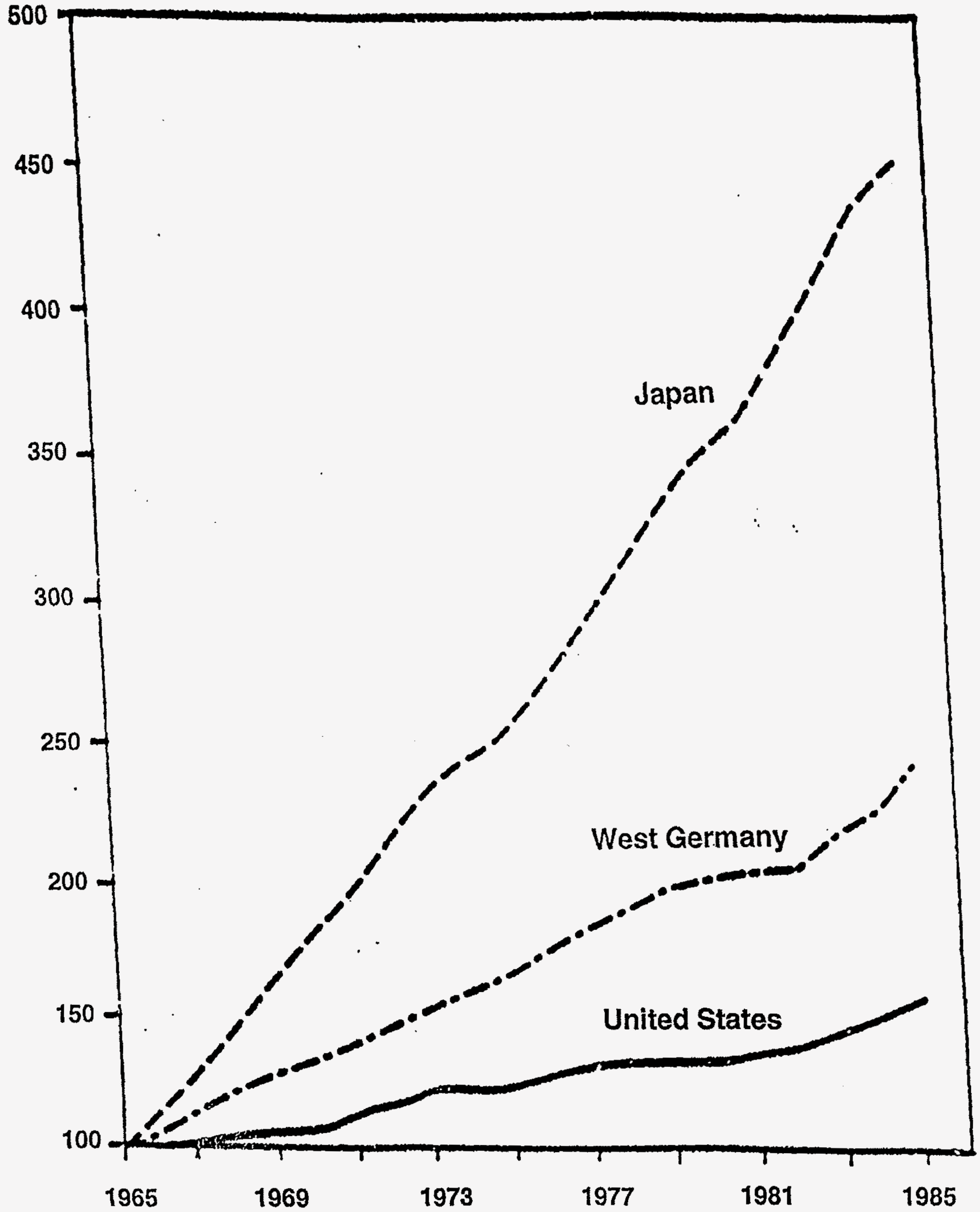


Figure 26. Status and Trands of Semiconductor Technology in Japan and the U.S. [122]



Source: U.S. Dept of Labor Bureau of Labor Statistics Office of Productivity and Technology: 1985

Figure 27. Manufacturing Productivity, 1965-85 [122]

F. Actions Bolstering Defense Industrial Competitiveness

In recognition of the absence of any coordination mechanisms between defense planning and private sector industrial planning, the Under Secretary of Defense for Acquisition, in July 1988, recommended an action plan to the Secretary of Defense that included six strategic thrusts: (1) forging the right relationship with industry, (2) establishing industrial strategic plans, (3) improving the acquisition system, (4) developing manufacturing capabilities concurrent with the development of weapon systems, (5) strengthening the skill base required to meet tomorrow's defense needs, and (6) improving the policy process. Specific actions taken by the Under Secretary of Defense for Acquisition was establishing the DoD Defense Manufacturing Board, modeled after the Defense Science Board, and by working with the National Academy of Sciences, arranged to have a nondefense counterpart organization called the Manufacturing Strategy Committee. The recommendations acknowledged the low status of manufacturing in general:

> "The attitude in the United States toward manufacturing and manufacturing technology is somewhat negative. American universities have little to offer in these fields. Even within the manufacturing firm, research and design engineers are perceived to have more prestige than manufacturing engineers. One result is that the manufacturing function does not compete effectively for high-quality personnel. (Conversely, the Japanese have a high regard for manufacturing and are totally committee to innovation in both process and product). These attitudes (and resultant rewards systems) toward manufacturing careers often prevent the best people from beginning or sustaining careers in manufacturing." [125]

The same year (1988) the Under Secretary of Defense for Acquisition made his recommendation, DARPA established the Concurrent Engineering Center at West Virginia University to provide a national resource devoted to designing, developing, and promoting concurrent engineering technologies.

In 1989, the Institute for Defense Analysis (IDA) reported the results of a study for the Assistant Secretary of Defense for Production and Logistics to determine the benefits of concurrent engineering in providing products of improved quality at lower cost in shortened product cycle. The IDA team reviewed the results of the 1987 DARPA workshop on Concurrent Engineering and conducted two workshops on this subject in 1988 to define concurrent engineering, and describe how companies were applying concurrent engineering techniques. Six companies were selected for detailed case studies with results summarized in Figure 28. Although pitfalls were found in the process, IDA concluded that a successful strategy could be based on concurrent engineering and made seven recommendations to the Secretary of Defense for implementing such a strategy. [126]

As a follow-on to the IDA study, the Defense Science Board Task Force focused on the areas of Integrated Product and Process Development (IPPD) and dual use in manufacturing in the 1993 report Engineering in the Manufacturing Process under the chairmanship of Dr. Kent Brown and Mr. Noel Longuemare. [127] The task force was organized into three subgroups to consider:

> (1) requirements for early consideration on manufacturing processes in the S&T environment, (2) the uses of advanced modeling and simulation in the IPPD phase, and (3) opportunities for increased use of best commercial products, practices and capabilities [124]. The key recommendation was that DoD institute a process that "focuses from the outset of development on improving the manufacturing process, that uses new tools in modeling and simulation, that takes advantages of commercial products, processes, and capabilities. The new process steps needed to implement integrated product- process development in the S&T phase is shown in Figure 29 and the benefits in Figure 30. As a result of the Board's recommendation, the Secretary of Defense issued a memo, 10 May 1995: "1 am directing a fundamental change in the way the Department acquires goods and services. The concepts of IPPD and IPTs shall be applied throughout the acquisition process to the maximum extent possible." [128] The work of the Defense Science Board was continued with the publication of a report of Defense Manufacturing Enterprise Strategy. [129]

The Defense Science Board Task Force on Defense Manufacturing Enterprise strategy identified government policies that impeded lean manufacturing, and recommended changes leading to world-class production, including strategies to break the cost-volume relationships. The task force also recommended actions to reorient the acquisition workforce to these new manufacturing policies practices and procedures. The task force found that "what to do" was well documented, but the barriers that prevented the implementations of prior recommendations were (1) performance-driven program definition, (2) cost-based contracting, (3) expensive and sluggish design, and (4) risk aversion procurement. [129]

The task force found that the principal reason the prior recommendations on manufacturing, acquisition, and industrial management had no impact was the lack of a process. The recommendations were therefore focused on "how to" implement change, rather than "what to do" in the entire enterprise. Special emphasis was placed on the term "enterprise" that was defined as having three meanings: a business organization, a systematic purposeful activity, and readiness to engage in daring action, initiative.

Case Study	Cost	Schedule	Quality
McDonnell Douglas	60% savings on bid for reactor and Missile Projects	Significant savings (reduction from 45 weeks to 8 hours) in one phase of high-speed vehicle preliminary designs; 18 months saving of TAV-88 design	Setup reduced 58%, rework cost reduced 29% and non-conformance reduced by 38%; weld defects performance unit decreased by 70%; 68% fewer changes on reactor; 68% fewer drawing changes on TAV-88
Boeing Ballistics Systems Division	Reduced labor rates by $28/hour; savings 30%below bid	Part and materials lead-time reduced by 30%; one part of design analysis reduced by over 90%	Floor inspection ratio decreased by over 2/3; material shortages reduced from 12% to 0; 99% defect-free operation
AT&T	Cost of repair for new circuit pack production cut at least 40%	Total process time reduced 46% of baseline for SESS	Defects reduces by 30% to 87%
Deere & Company	30% actual savings in development cost for construction equipment	60% savings in development time.	Number of inspections reduced by 2/3
Hewlett-Packard Co. Instrument Division	Manufacturing costs reduced by 42%	Reduced development cycle time by 35%	Product field failure rate reduced 60%. Scrap and rework reduced by 75%.
IBM	Product direct assembly by labor hours reduced 45%	Significant reduction in PMT design cycle; 40% reduction in electronic design cycle.	Fewer engineering changes. Guaranteed producibility and testability.

Figure 28. Cost Schedule and Quality Benefits of Concurrent Engineering [126]

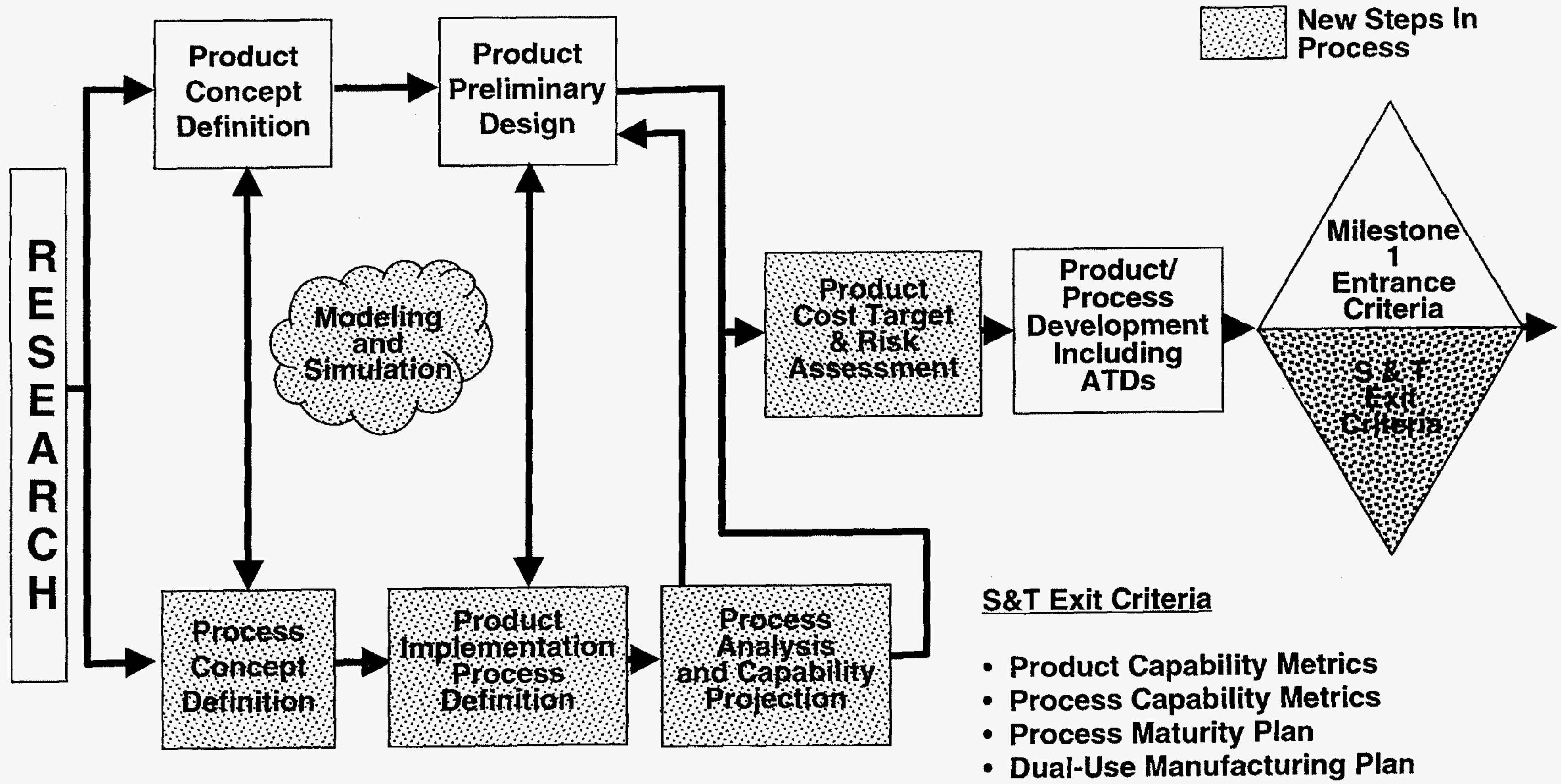


Figure 29. Recommended Approach – IPPD in the S&T Phase [127]

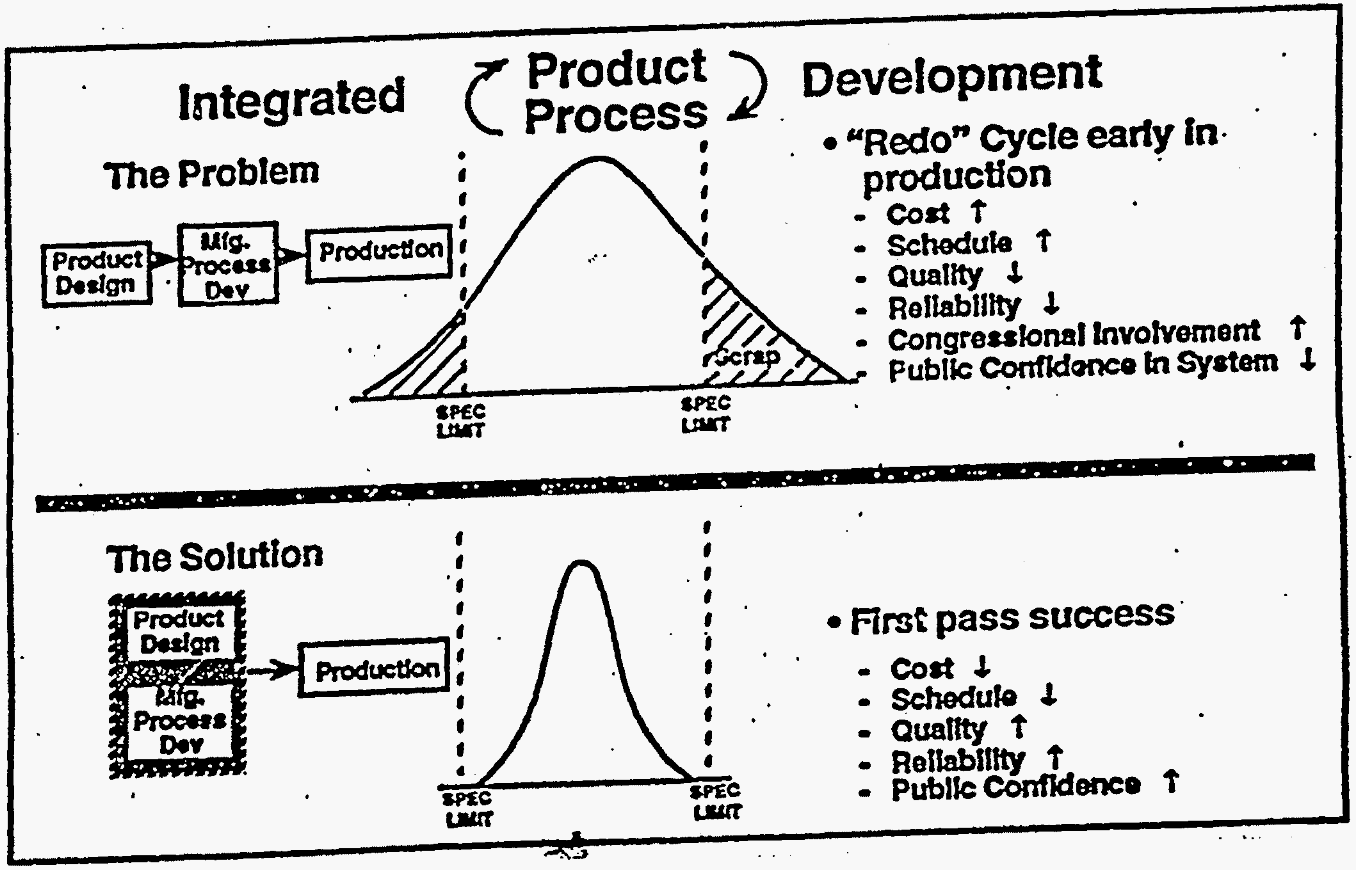


Figure 30. Integrated Product and Process Development [127]

9

XI. THE MIMIC PROGRAM

A. Outline of the MIMIC Program

The overall program structure of MIMIC featured four phases shown in Figure 31. A 1-year definition or study phase, a materials and technology development phase of 36 months followed by a second phase of 36 months that featured a higher level of integration than Phase 1, and capitalized on the lessons learned from Phase 1. Phase 3 was conducted in parallel with Phases 1 and 2, and provided supporting research in automated testing, device and circuit modeling to improve the computer-aided design process and materials research. The centralized management of the VHSIC program is shown in Figures 32 and 33. The MIMIC program drew heavily on the lessons learned from the VHSIC program, but had a similar centralized management structure shown in Figure 34.

Forty-eight contractors in 16 teams participated in the Phase 0, which was a study phase only to identify the specific problems to be overcome, and recommended approaches to overcome these problems. To achieve this required that existing design and fabrication processes and materials be characterized as the basis for recommending improvements. Part of the Phase 0 study was to identify supporting research tasks for Phase 3 conducted in parallel with Phases 1 and 2. To provide the framework for the study phase, generic systems were identified in the Phase 0 BAA in the following categories by service: Radar, Electronic Warfare, communications, and Smart Weapons. The Phase 0 efforts were completed in February 1988.

Four contractor teams were selected to participate in Phase 1 that was initiated in March 1988, with the objective of exercising and building upon the current state-of-the-art in MIMIC technology (Figs. 35 through 38). Each team member provided expertise in one or more areas of MIMIC product development: material growth, wafer processing, testing, device and circuit modeling, computer-aided designs, and manufacturing, packaging and systems integration. A key to reducing the cost of MIMIC chips was to minimize the cut-and-try processes in designing, fabricating, and testing MIMIC chips by putting computer-aided design on a more scientific basis, beginning with the initial design and the development of software tools that provided realistic models on performance. The projected products for this phase were not only approximately 80 MIMIC chips for the variety of application identified in the Phase 0, but 23 types of functional modules using these chips, and 16 brassboards demonstrating systems using these modules. The Phase 2 represented an effort analogous to Phase 1, but with a strong emphasis on advancing the state-of-the-art and increasing the complexity of the functions that could be fabricated on a single chip. Special emphasis was placed on the development and characterization of hetrojunction devices that are formed between semiconductor materials of different compositions and bandgaps such as GaAs/AlGaAs and InGaAs/ImP, in contrast to MESFETS that have junctions formed from similar materials. The most notable examples of such hetrojunction devices are the HEMT and the HBT. The GaAs HEMT represented an advancement in the state-of-the-art of the GaAs MESFET that provided low noise, high gain, and high power over the entire millimeter wave band. The advantages offered by the HBT for millimeter and microwave applications are as power amplifier oscillators and mixers. Both of these devices were compatible with the MIMIC processing technology and were particularly important for smart weapons applications of MIMIC that required the higher millimeter wave frequencies.

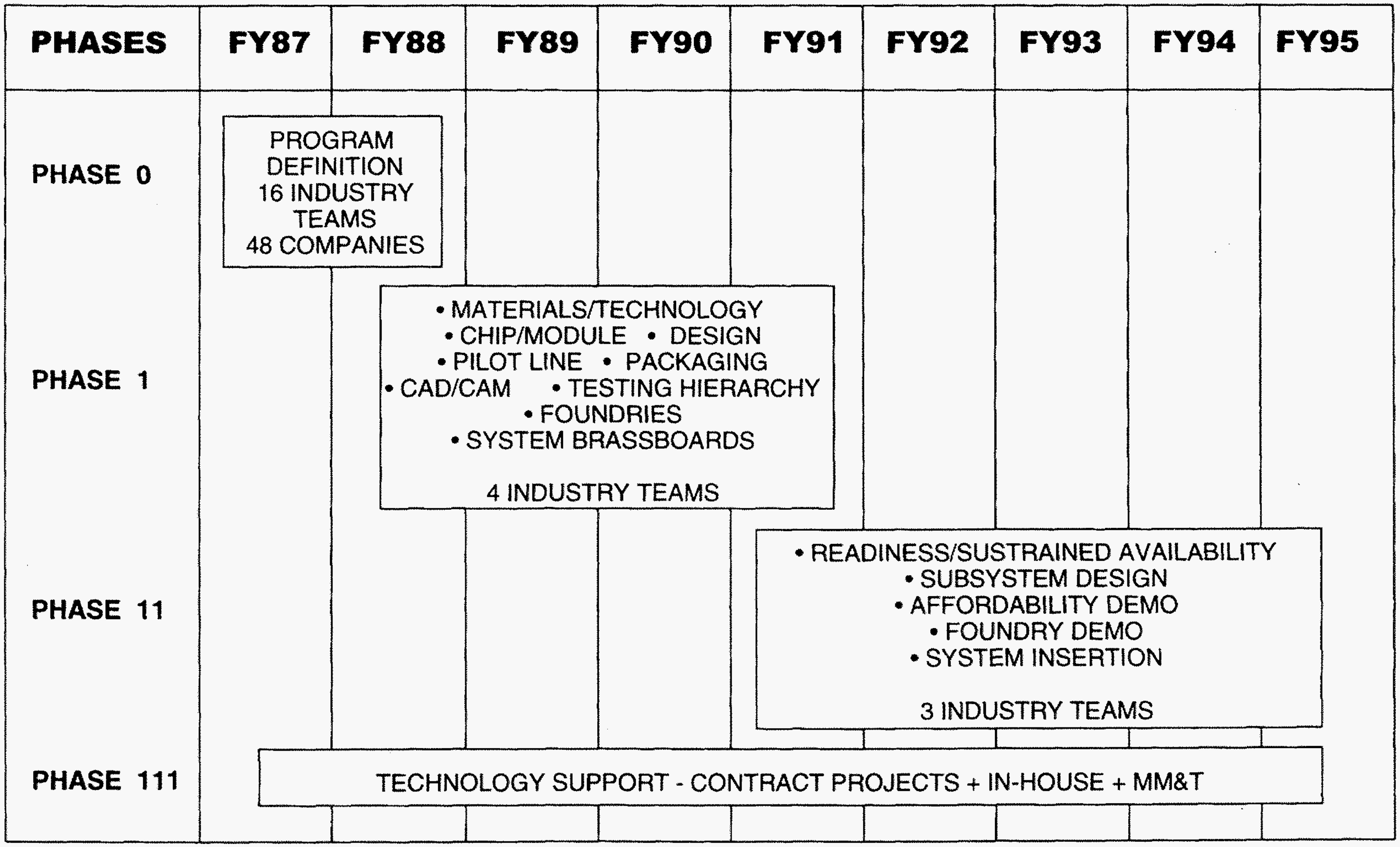


Figure 31. Roadmap of the MIMIC Program [135]

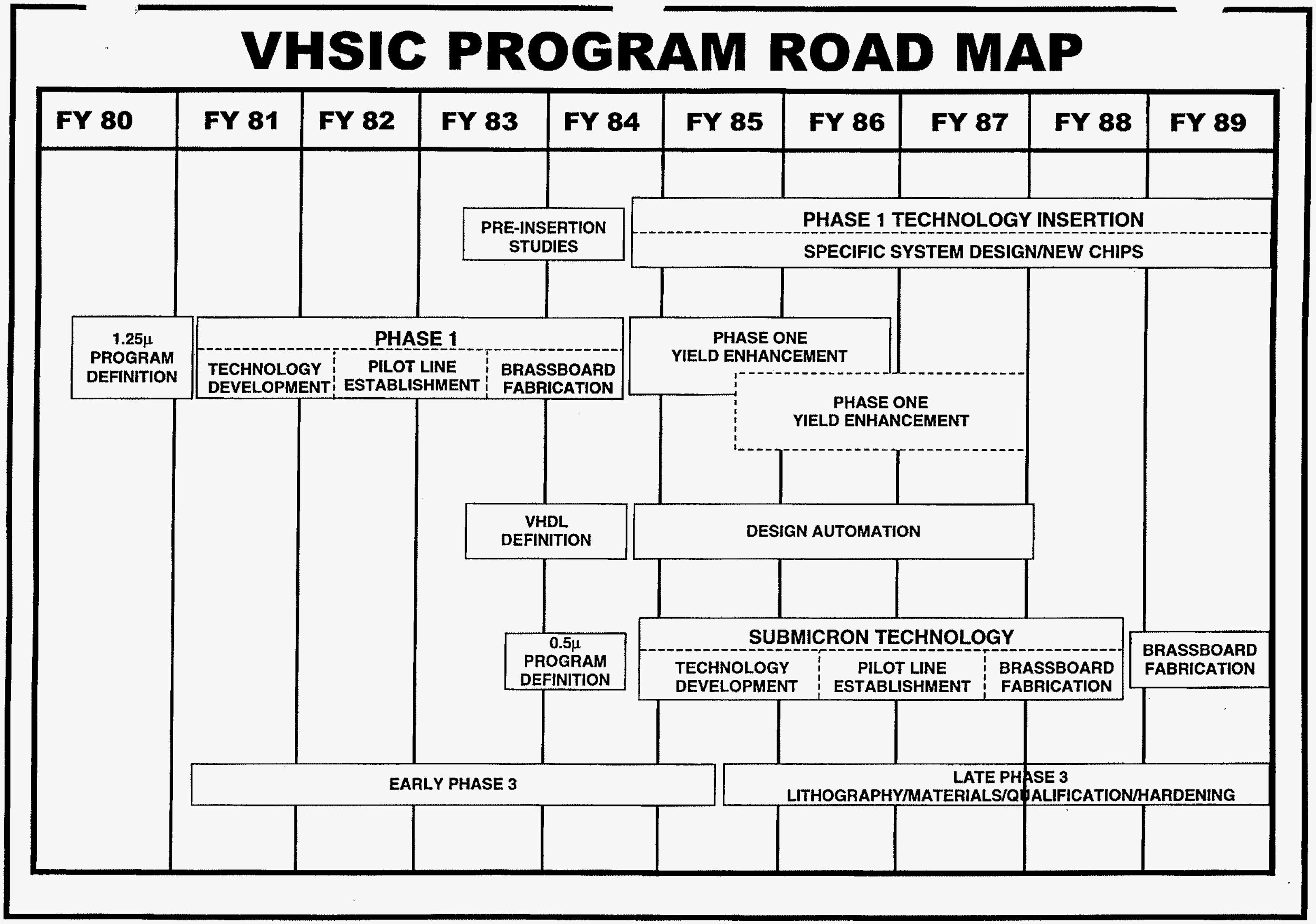


Figure 32. VHSIC Program Road Map [120]

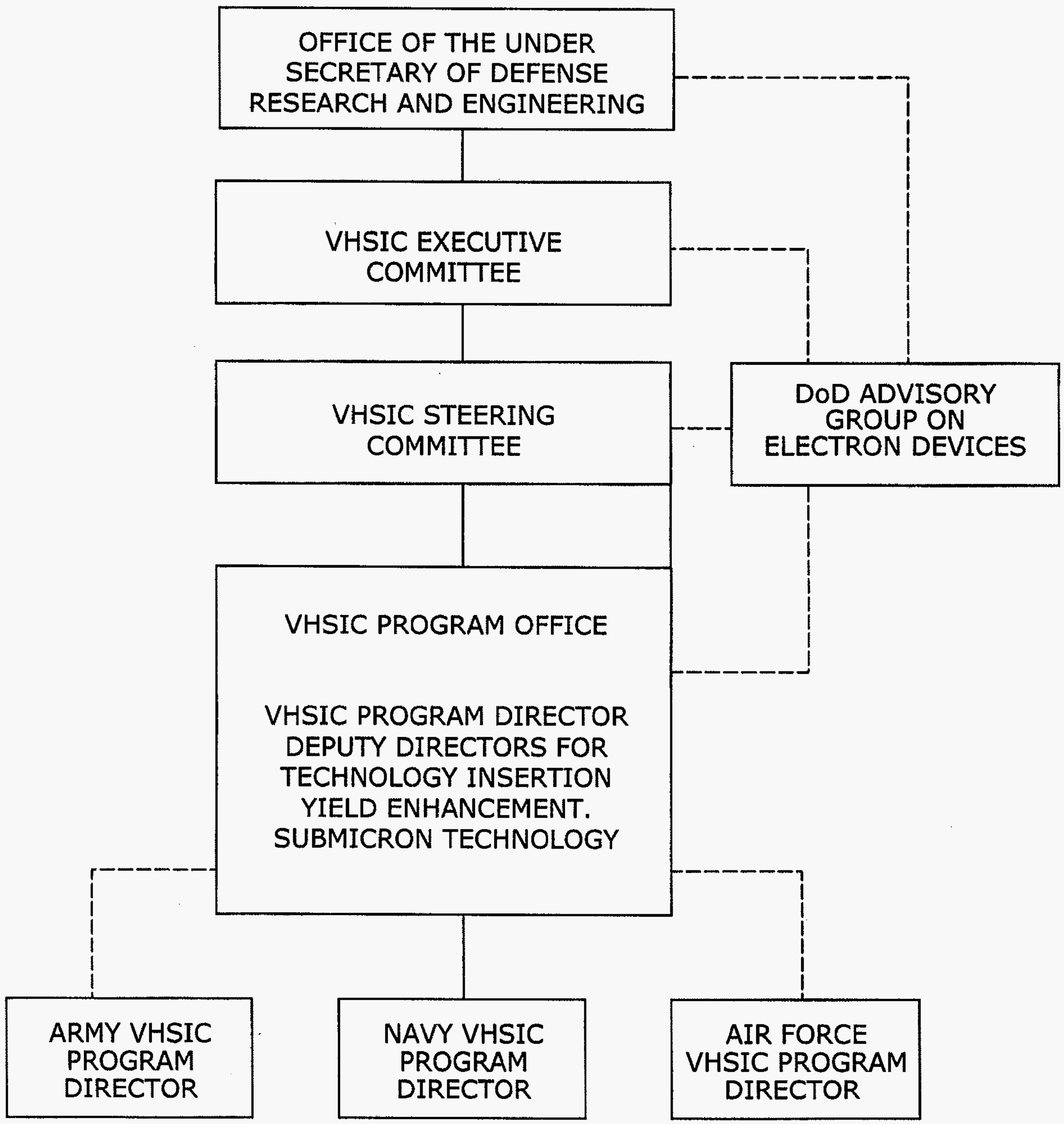


Figure 33. DoD VHSIC Program Office Structure [120]

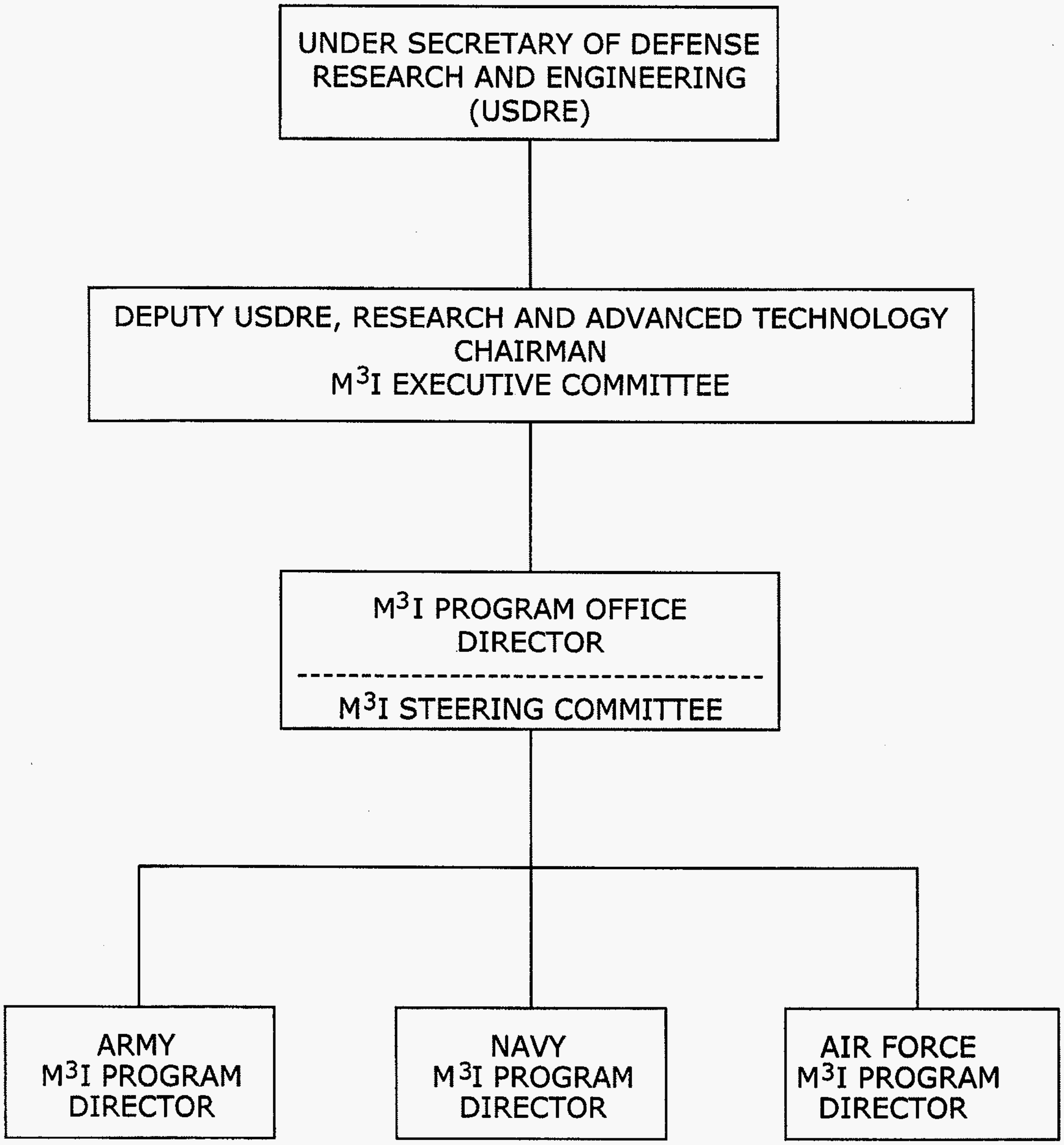


Figure 34. DoD M^3I Program Office Structure [107]

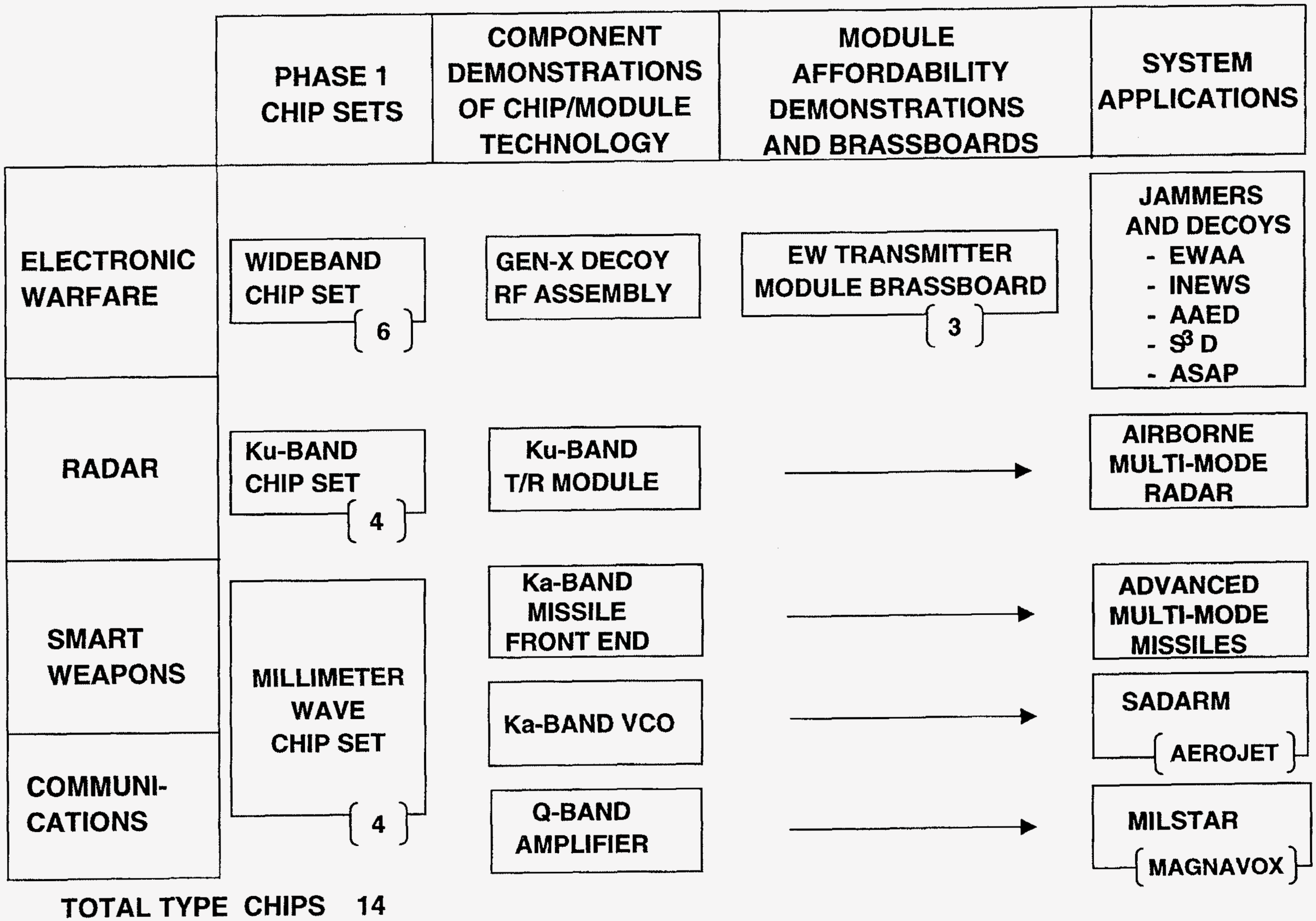


Figure 35. Raytheon/TI Team's Hardware Demonstration [130]

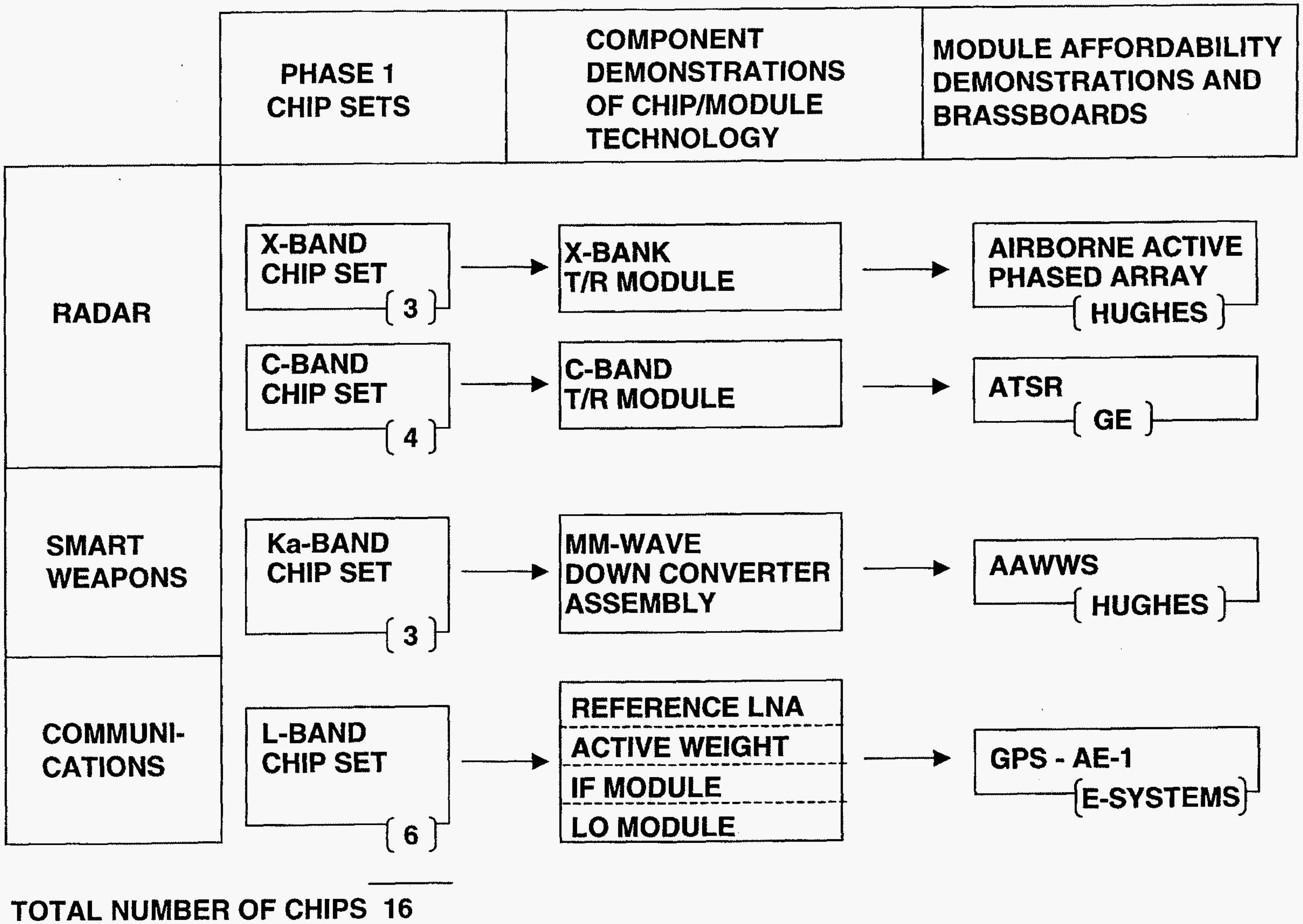


Figure 36. Hughes Team's Hardware Demonstration [130]

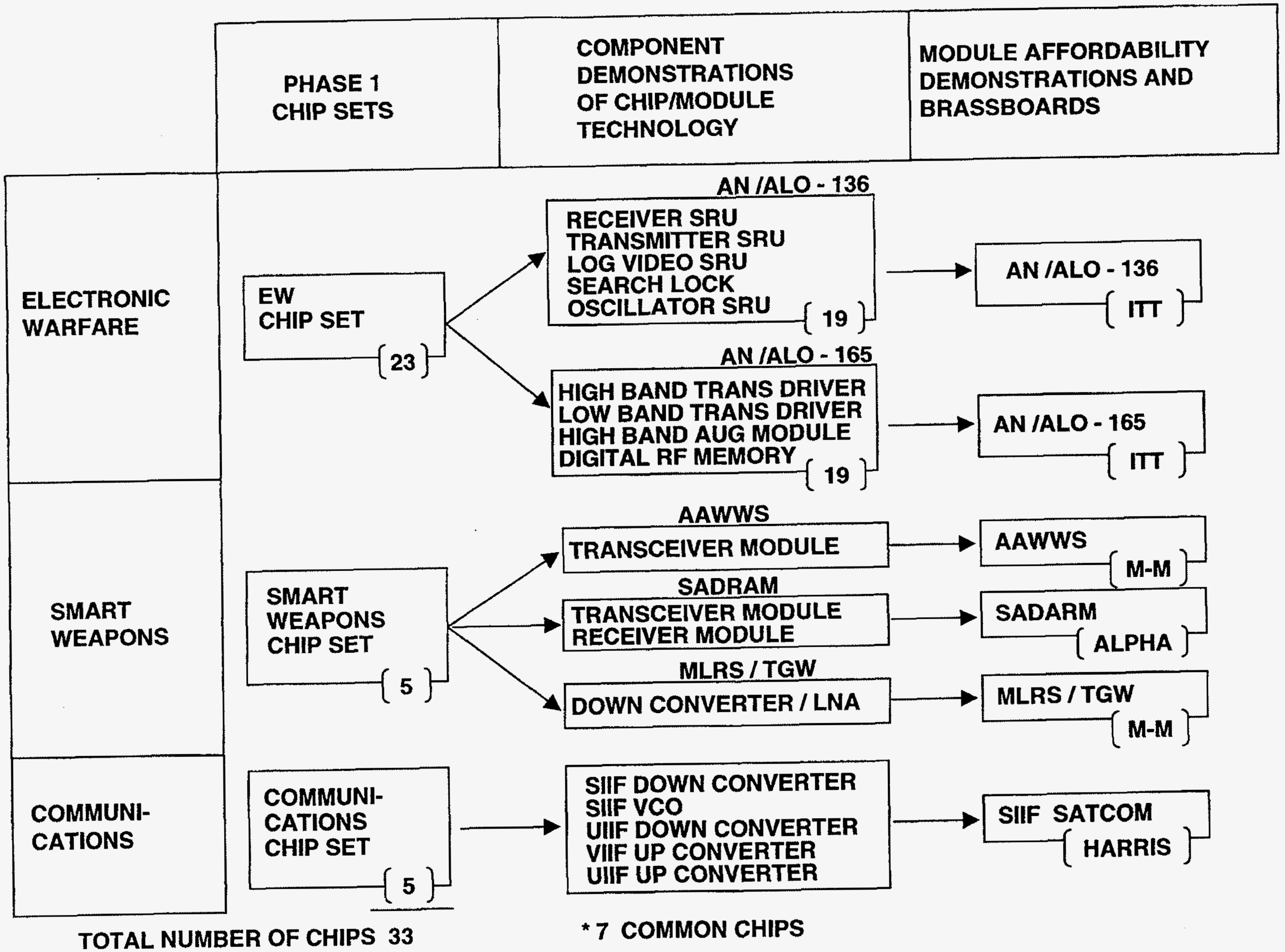


Figure 37. ITT Martin Marietta Team's Hardware Demonstration [130]

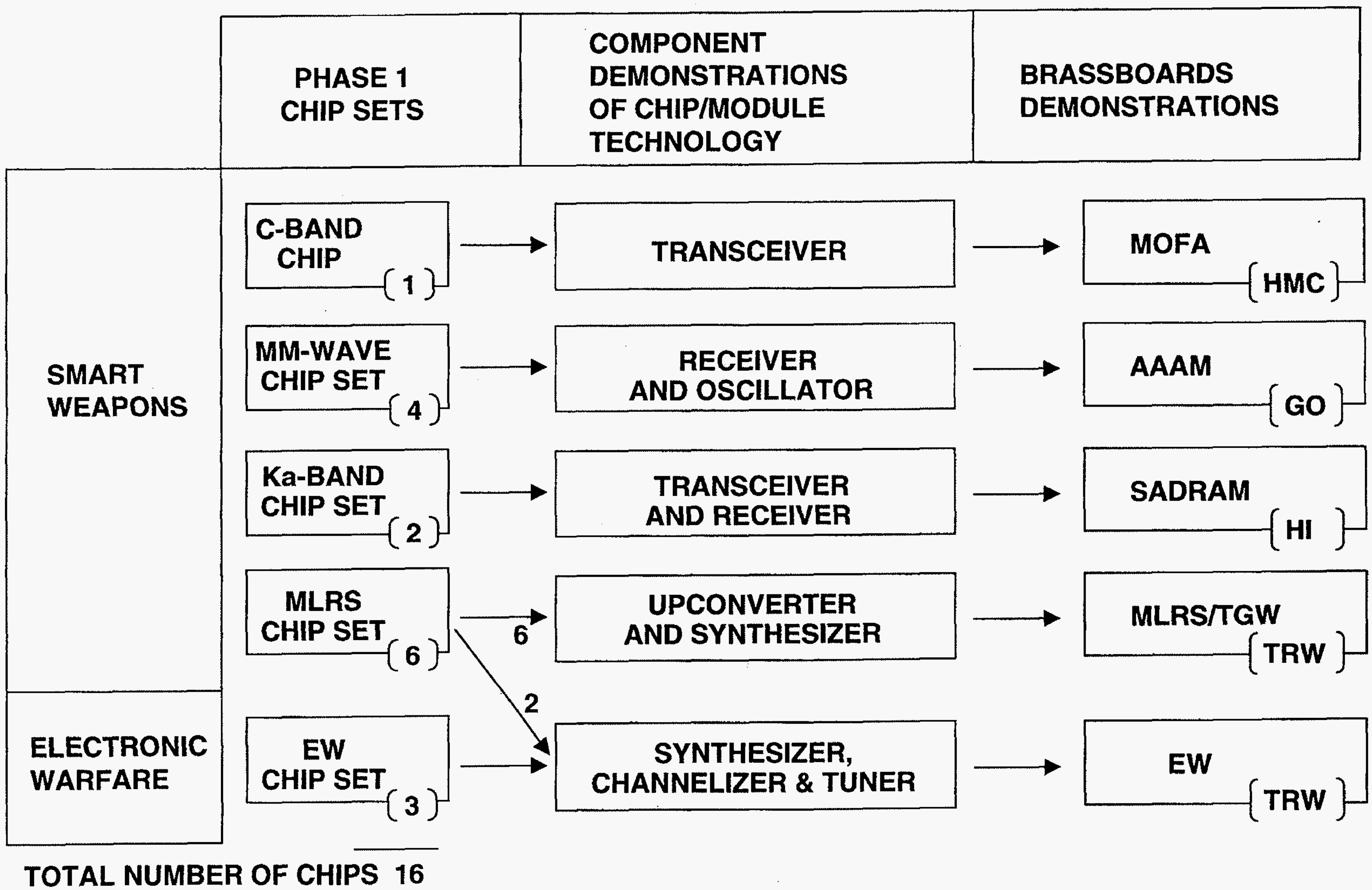


Figure 38. TRW Team's Hardware Demonstration [130]

Phase 3 was conducted in parallel with Phases 1 and 2 and provided the supporting research in device and circuit modeling to improve the computer-aided design process, novel circuit concepts, materials processing, fabrication processes, integration and packaging and metrology and testing. The early involvement of the NBS ensured that the latter category would receive strong efforts by both Government and industry. More than a third of the Phase 3 efforts were on automated testing that included: Optical diagnostics for characterizing wafer quality (AT&T); techniques for on-wafer testing of MIMIC chips (Ball Aerospace); and wafer testing (M/A-COM). Complementing the task funded by Phase 3 (DARPA) were tasks funded by the NBS and the NBS-Industrial Consortium. The success of the MIMIC program can be attributed in a large measure to the participation of NBS in the early phases of program formulation.

Both Mr. E. D. Maynard, Jr., and Mr. Eliot Cohen and the services provided extensive reporting in the open literature on the objectives, plans, progress, and benefits over the life of the program. [130, 131, 132, 133, 134, 135, 136, 137, 138, 139, 140, 141, 142, 143, 144] Mr. E. D. Maynard provided the reason for MIMIC, program structure, program objectives, and expected payoff at the 1986 IEEE Microwave and Millimeter Wave Monolithic Circuits Symposium. [131] Mr. Maynard observed that DoD applications for MIMIC were dominant, and expected to remain dominant.

At the end of Phase 0, Cohen announced that the first development phase of MIMIC was scheduled to start April 1988, with the objective of meeting first close-in system needs, and then providing an adequate longer term MIMIC component capability for the 1990s and the early 21st century. [120] Cohen also underscored the role of the Government in-house laboratories in carrying out supporting research, test, and evaluation, as well as program planning, proposal evaluation, and contract monitoring.

On 20 May 1988, 4 contractor teams consisting of 26 companies were awarded 225 million in contracts with admonition by Cohen that there was a constant necessity to share information. By December 1989, of the planned 79 Phase I chip types, 12 had been fabricated and demonstrated within the first 6 months of the program. [130] Mr. Cohen outlined four key tasks the contractors had to achieve in order to meet program objectives: (1) robust processing capabilities, (2) highly automated wafer testing, (3) comprehensive computer-aided design, and (4) modem production discipline. [130] Even before Phase I was completed, MIMIC was already finding application in DoD systems. At the completion of Phase 1, Cohen summarized the progress in smart weapons, electronic warfare, radar and communications. During this phase, both Raytheon and Texas instruments were producing .5 to 4 GHz IF amplifiers for the Navy/Air force HARM missile. MIMIC technology was under development at the end of Phase I for AMRAM, LONGBOW and MLRS-TGW. For electronic warfare applications, wideband MIMIC power amplifiers had been developed with efficiencies about twice those achieved previously, and packages made from metal matrix composites with the promise of lowering packaging costs to as little as $5.10 for a Phase I demonstration in the Generic Decoy (GEN-X). GEN-X was already in use in Desert Shield. The ITT/Martin MIMIC Phase I Team developed improved hardware for the Army AN/ALQ-13 6 helicopter jammer and the Navy's AN/ALGORITHMS-163 tactical fighter jammer. Over 23 chip types had been developed for 12 modules to upgrade these systems. The primary MIMIC chip type to be used in the Counter Battery Radar was being produced by General Electric (GE), Hughes Aircraft Co., Harris Microwave, AT&T, and

MA-COM. The Hughes/GE Team was also developing chips, modules and a brassboard demonstration for airborne phased array radars. For Global Positioning Systems, Hughes Aircraft Company, with team members E-Systems, were developing the next generation antenna electronics that was projected to reduce parts cost by 50 percent, package size by 79 percent, and weight by 65 percent.

Although the principal responsibility for executing the program was with the contractor teams, Mr. Cohen highlighted the role of the DoD in-house laboratories in working with the contractor teams. [137] At the 1998 IEEE Microwave and Millimeter Wave Monolithic Circuits Symposium, Mr. Cohen also summarized the contractor findings and recommendations in materials, chip design approaches, CAD/CAT/CAM, Packaging, and Test. [134]

At the close of the program, Cohen focused on the challenges of developing MIMIC chips and multi-chip module assemblies for application in electronically scanned arrays. Cohen identified eight key factors compacting recurring costs. At the module and multi-chip assembly, Cohen found that the key to reducing costs for both the recurring and non-recurring costs was improved computer-aided design capability combined with low-cost assembly and test methods. The need for more research in packaging materials was highlighted, and a number of candidate materials were discussed. After concluding that the T/R module made up approximately 50 percent of the overall active electronically scanned array cost, sub-array manufacturing cost, and array integration about 10 percent, Cohen concluded that potentially the greatest opportunity for savings was improved computer-aided design capabilities that would sharply reduce the MCA design cycle time and improve "first pass" design success.

In 1995, Eliot Cohen summarized the accomplishments in the final year: (1) a solid infrastructure for microwave and millimeter wave monolithic integrated circuits had been accomplished, (2) two substrate vendors were profitable and selling material world-wide, (3) two computer-aided design vendors were profitable and dominated the world market for CAD, (4) more than six MIMIC program participants were providing foundry services world wide. In the area of materials, gallium arsenide boule size had missed from 3 to 4 inches and wafer characteristic and uniformity had greatly improved. During Phase 2 of the program, the maturing of new manufacturing processes had allowed the development of devices that reduced feature size from .5 to .1 micron for the MESFET, as well as the HEMT and HBT. The improvements in commercially available test stations for both on-wafer testing and module testing allowed significant reduction in a major cost in the MIMIC process.

B. Productivity of the MIMIC Program

The unique cultural setting in which the MIMIC program was planned and executed had a catalytic effect that made the program itself a mechanism for effecting cultural change. The productivity of the program as a result of these changes can be traced to: (1) the unique program architecture, (2) the elevation of process development in importance in the product development life cycle, (3) the execution of a top level strategic planning process that drew on good ideas from all sectors of the economy, and (4) the recognition that the health of the American semiconductor industry was an essential factor in meeting future defense needs. The influence of these factors can be traced in the large volume of intellectual products including journal articles, books and patents that can only be briefly mentioned here.

The productivity of the MIMIC program is reflected in several seminal volumes published by IEEE: Modulation Doped Field Effect Transistors: Principles Design and Technology, Edited by Heinrich Daembke, was conceived as an extension or supplement to the IEEE Press book Low Noise Microwave Transistors and Amplifiers, Edited by H. Fukui. A second volume, Modulation - Doped Field Effect Transistors:

Applications and Circuits provide a survey of the application of MODFETS in analogy and digital circuits with approximately 100 papers organized into three parts: MODFETS in analog systems, MODFETS in digital circuits, and Optoelectronic applications. The new device has been given several names by different research institutions that were contributors to its development. High Electron Mobility Transistor (HEMT); Two-Dimension Electron-Gas Field Effect Transistor (TEGFET); Selectively Doped Hetro-FET (SDHT); and Hetro-Field-Effect Transistor (HFET). A third IEEE Volume: Modulation - Doped Field Effect Transistors: Principles, Design and Technology also contains approximately 100 papers organized in 15 sections in the following four parts: Introduction, GaAs MODFETS, Numerical Simulation of MODFETS; and Impact of New Materials and Structures. In addition, a large number of books in the Artech House Library contain MIMIC as a topic.

Patents also provide another measurement of the productivity of the MIMIC program. Although a direct correlation between the growth in MIMIC related patents (Fig. 39), and growth in MESFET patents (Fig. 40) and HEMTS (Fig. 41) and the DoD MIMIC program cannot be established, it is clear that the program provided a stimulus for this growth. The data for Figures 39 and 40 was produced from searching the CLAIMS/US Patents database. CLAIMS/U.S. Patents database provides access to over 2.9 million U.S. issued patentns by the U.S. Patent and Trademark office since 1950. The CLAIMS patent databases covers all areas of technology patentable in the U.S.. All the terms below were searched in the basic index fields. The basic index fields searches title, abstract, exemplary claims, text of claims or other claims. The MIMIC-related patents includes the term MIMIC (Microwave and millimeter Monolithic Integrated Circuits) with supporting search terms "gallium arsenide," "monolithic microwave integrated circuits," "millimeter wave integrated circuits," "Schottky-barrier-diode," or "Gunn-diode." The MESFET-related patents include those in which the terms MESFET (Metal-Semiconductor Field Effect Transistor) with supporting search terms of "gallium arsenide" "schottky-barrier." The MESFET can be fabricated in monolithic form with other passive circuits elements, or in discrete form as a single device, so the chart would include both. The HEMT related patents includes those for which the term HEMT (High Electron Mobility Transistor) or analogous terms: Two-Dimensional Gas Field Effect Transistor (TEGFET), Modulation Doped Field Effect Transistor (MODFET), Selectively-Doped Hetro-FET, SDHT, Heterostructure Field Effect Transistor, High Multilayer Heterojunction Transistor, HIGFET, or Hetro-Field Effect Transistor (HFET) with supporting search terms "GaAs" "GaAs/ARGaAs" "pseudomorphic Heterostructure Electron Mobility," "H-FET" or "PHEMT." In GaAs/AlGaAs "molecular beam epitaxyll," "metal organic-chemical vapor deposition." The HEMT or MODFET represents an extension of the capabilities of the MESFET as a result of its superior electron transport properties.

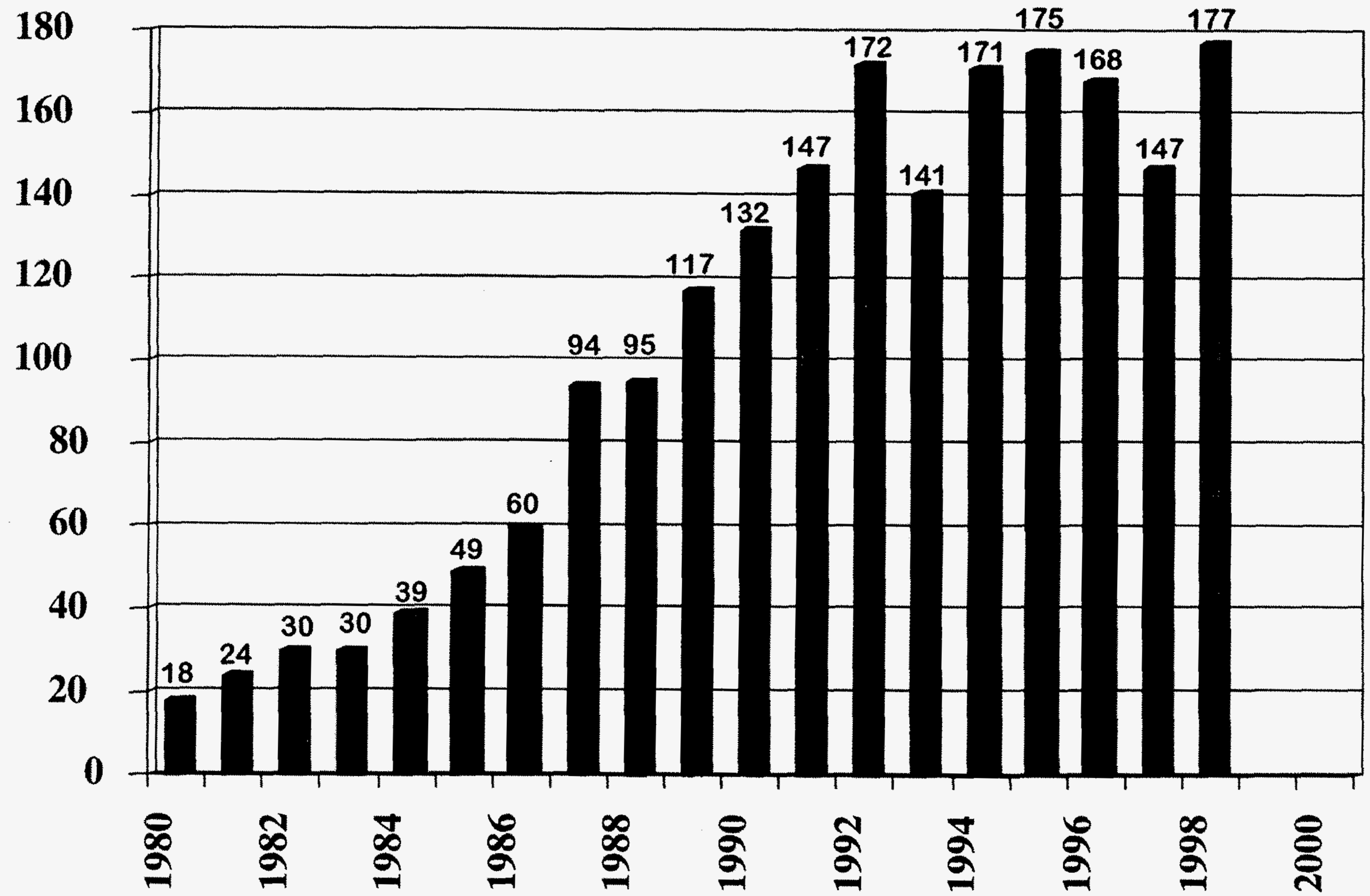


Figure 39. MIMIC Related Patents

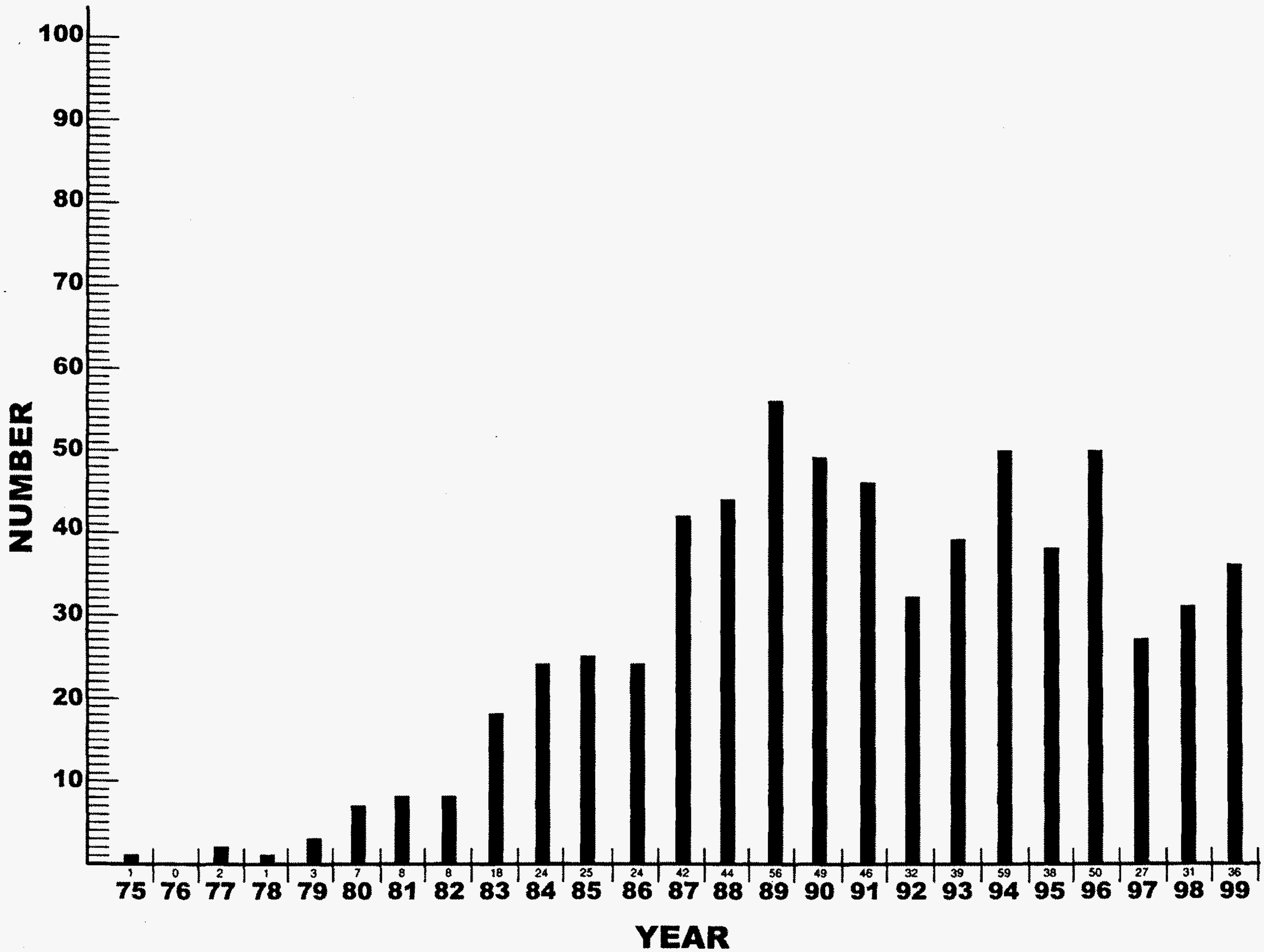


Figure 40. Patent Growth in MESFETS

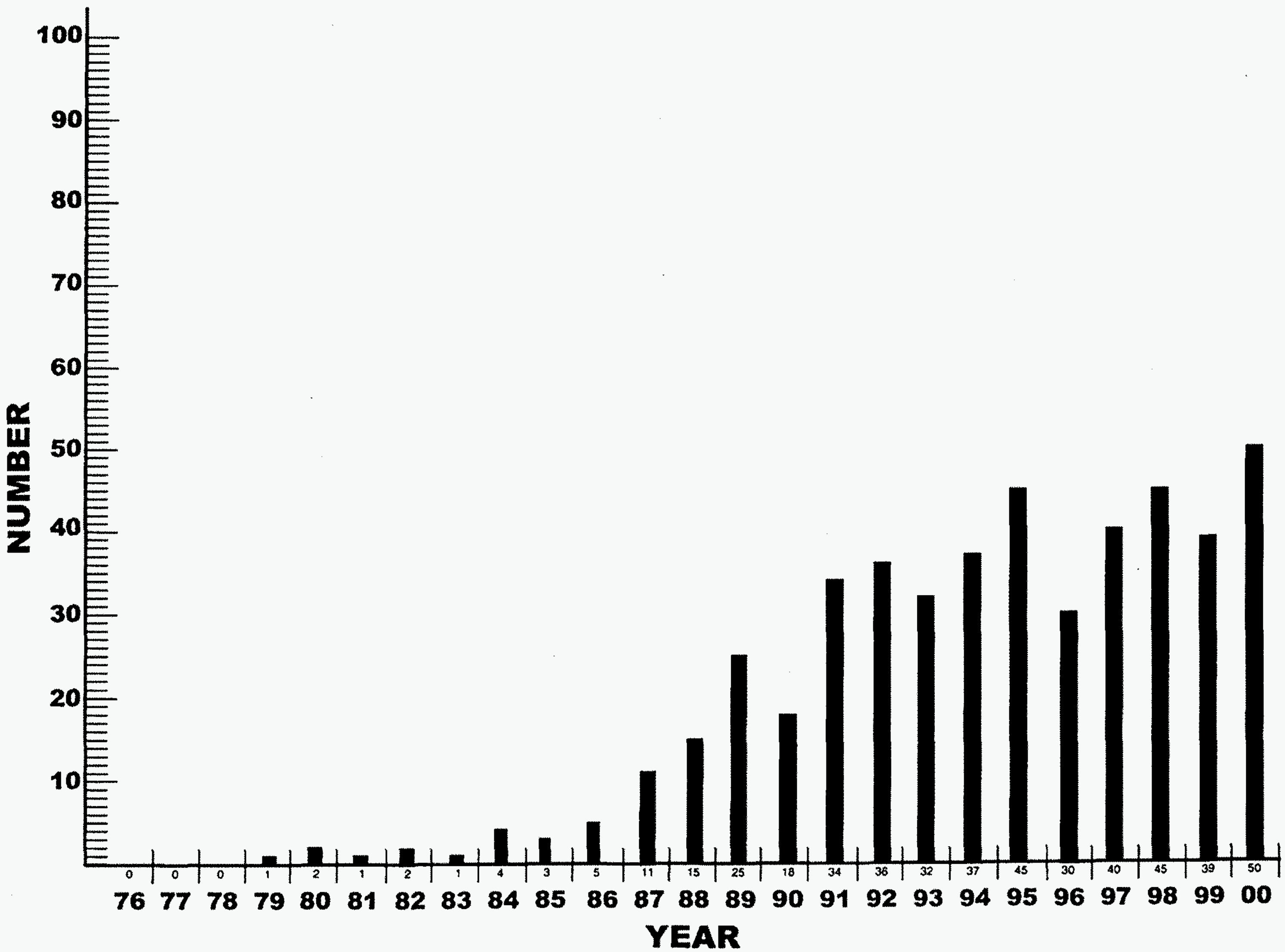


Figure 41. Patent Growth in HEMTS

XII. SCIENCE POLICY

A. Limitations of The Vannevar Bush Science Policy

The MIMIC program was formulated during this period when the loss of U.S. leadership in global markets brought about searching reexaminations of the limitations of Post-World War II science policy framed by Vannevar Bush. Bush saw basic research as the principal fountainhead of all progress that is "performed without thought of practical ends" and adds to the pool of general knowledge that "provides the means of answering a large number of practical problems." Although Bush saw an inherent tension between basic and applied research, progress was achieved by linear progression from the pool of general knowledge through applied research, product development, and manufacturing:

> "New manufacturing industries can be started and many older Industries greatly strengthened and expanded if we continue To study natures laws and apply new knowledge to practical Purposes." [2]

In the defense sector, the linear model provided the basis for the way the Defense Department categorized the different phases of the weapon acquisition process. This so-called "linear model" viewed basic research as the principal source of innovation, but in reality, it applies to a restricted set of conditions where the progression is from research breakthroughs to markets for radical discoveries rather than incremental advances. However, the U.S. was defeated in an area where technological innovation is market-driven in incremental steps.

The Council on Competitiveness identified a key U.S. weakness derived from the flawed science policy:

> "Much of the U.S. failure to exploit technology for commercial advantage for commercial lies in not adequately appreciating the importance of manufacturing and not properly balancing short-term and long-term goals. The neglect of manufacturing arose largely out of complacency of the 1950s and 1960s when the U.S. dominated international markets. Top managers began to focus on marketing and finance at the expense of manufacturing, and as a result, failed to manage the investments in worker skills, plant and equipment necessary for strong manufacturing capability. Today (1988) foreign companies are often beating U.S. companies not with low wages, but with more efficient manufacturing processes. For example, Japanese manufactures spend two-thirds of their R&D budgets on process innovations, while manufacturers spend only one-third." [145, 3]

The findings of the Council on Competitiveness was consistent with the results of other studies. A key to improving competitiveness was to compress the product development cycle. Bernard Slade explored this question with 21 professors and 200 senior executives. [146] Most of the academics attributed the decline in U.S. competitiveness to weakness in manufacturing, and as Figure 42 shows, 40.6 percent of the senior executives identified integrated design teams as the factor needed for shortening the product development cycle. Investing in total quality was at the top of the list for meeting future challenges (Fig. 43). Slade learned from a professional colleague the difference in the manner in which the design manufacturing linkage was managed in Japan and the U.S. The Japanese were puzzled by the

question from their American guest on how they handled "design for manufacturability." The question could only come from a culture that practiced "over the wall" coupling of design and manufacturing. Design and manufacturing were so well integrated in Japan that the term "design for manufacturability" had no meaning. Robust design achieves a balance between cost, reliability, and performance; a central goal of the MIMIC program.

B. Congress Examines the Limitations of the National Science Policy

In the charge to the House Committee on Science, the Speaker of the U.S. House of Representatives acknowledged on 12 February 1997, that the science policy framed by Dr. Vannevar Bush in 1945 was no longer valid, and the speaker requested "a new, sensible coherent, long-range science and technology policy." As a result, the committee held seven hearings, two roundtables, and encouraged interaction between the scientific and policy communities. A website was also set up to allow public participation. [147]

The flaws in the Bush policy have been examined by a number of scholars and may be summarized briefly as follows: the distinction between basic and applied research is no longer valid; the social sciences were not included in the Bush policy; Bush saw basic research as the principal source of innovation that generated a one-way flow of events and ideas in time that resulted in products and services to meet the needs of society, without considering the feedback effects on basic research. These points were brought out very well in the testimony, but some observers believe there is a general lack of awareness of how deeply the Bush model influences daily behavior in universities, industry, and Government.

The implication of the ideal that basic research is the principal source of innovation is that basic research is more intellectually demanding than what follows and, therefore, society should apportion rewards accordingly. The consequence of this was felt in the 1980s when it was revealed that a principal weakness in U.S. competitiveness in global markets was in manufacturing, and a lack of insight into the total product realization process. The response was a series of actions by the Congress, the Executive and the private sector in the 1980s to encourage technology development, promote partnerships, improved educational institutions, and increase productivity in the R&D process. In a 1988 report to the Secretary of Defense, the Under Secretary of Defense for Acquisition identified the weakness in Weapons development:

> "In large measure the inability of American managers to achieve results in manufacturing equal to those of Japanese mangers in the U.S. stems from management theory and practice, as taught in American universities (where for example, good management is management by financial control; good managers can manage anything, individual achievement is important, not teamwork; manufacturing is an unimportant function). Engineering schools in American universities also focus inadequately on manufacturing, training engineers for careers in product research and development. Few faculty members have industrial experience or expertise. Emphasis on specialization results in engineering professionals who all ill-equipped to understand total manufacturing systems." [125]

The science policy changes in the 1980s, and those leading to UNLOCKING OUR FUTURE in the 1990s have been characterized as "fine tuning," rather than a reaction to a crisis that leaves some observers wondering if there is a real understanding of the depth of the crisis. [147, 148]

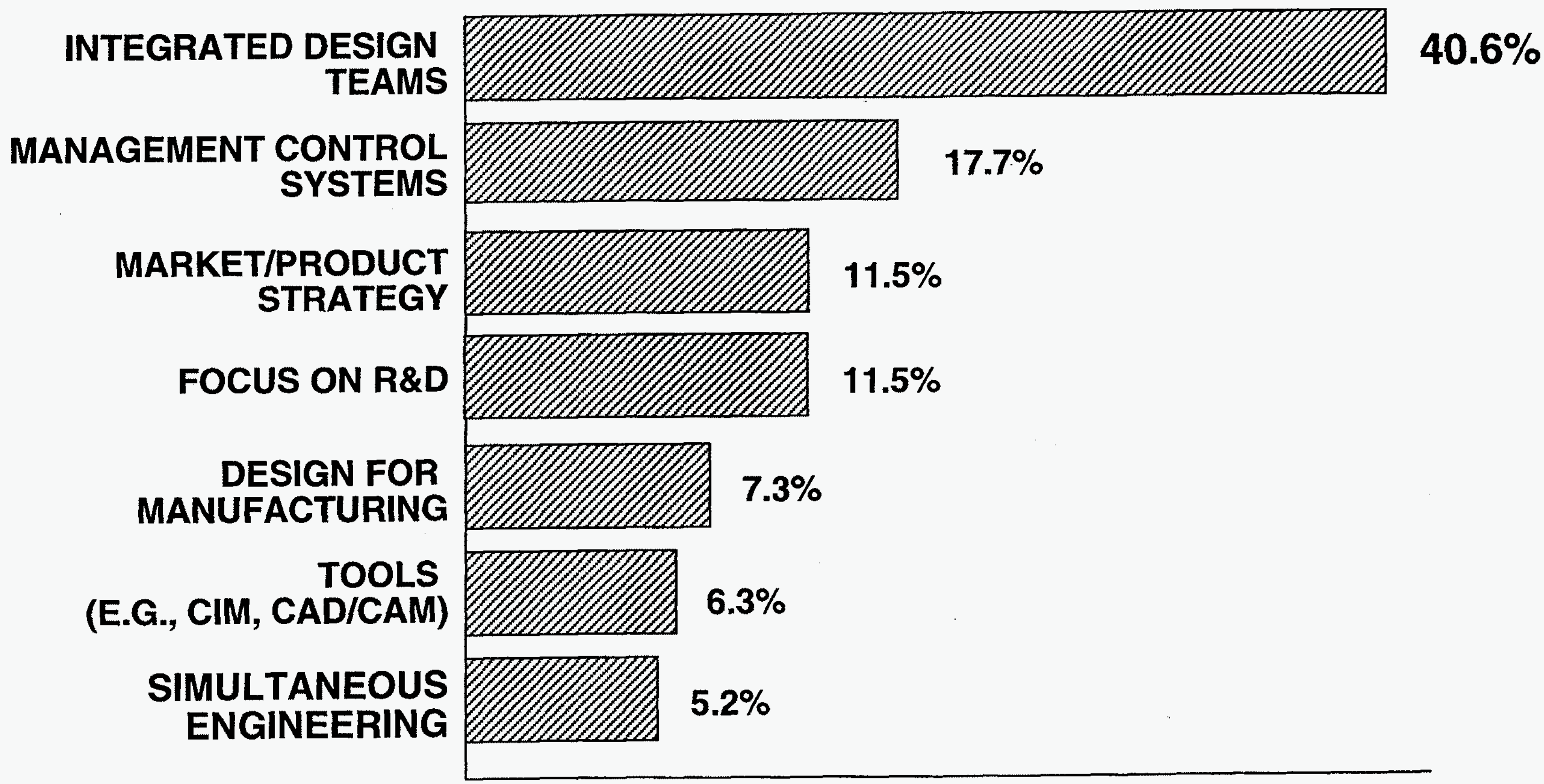


Figure 42. Factors for Shortening the Development Cycle [146]

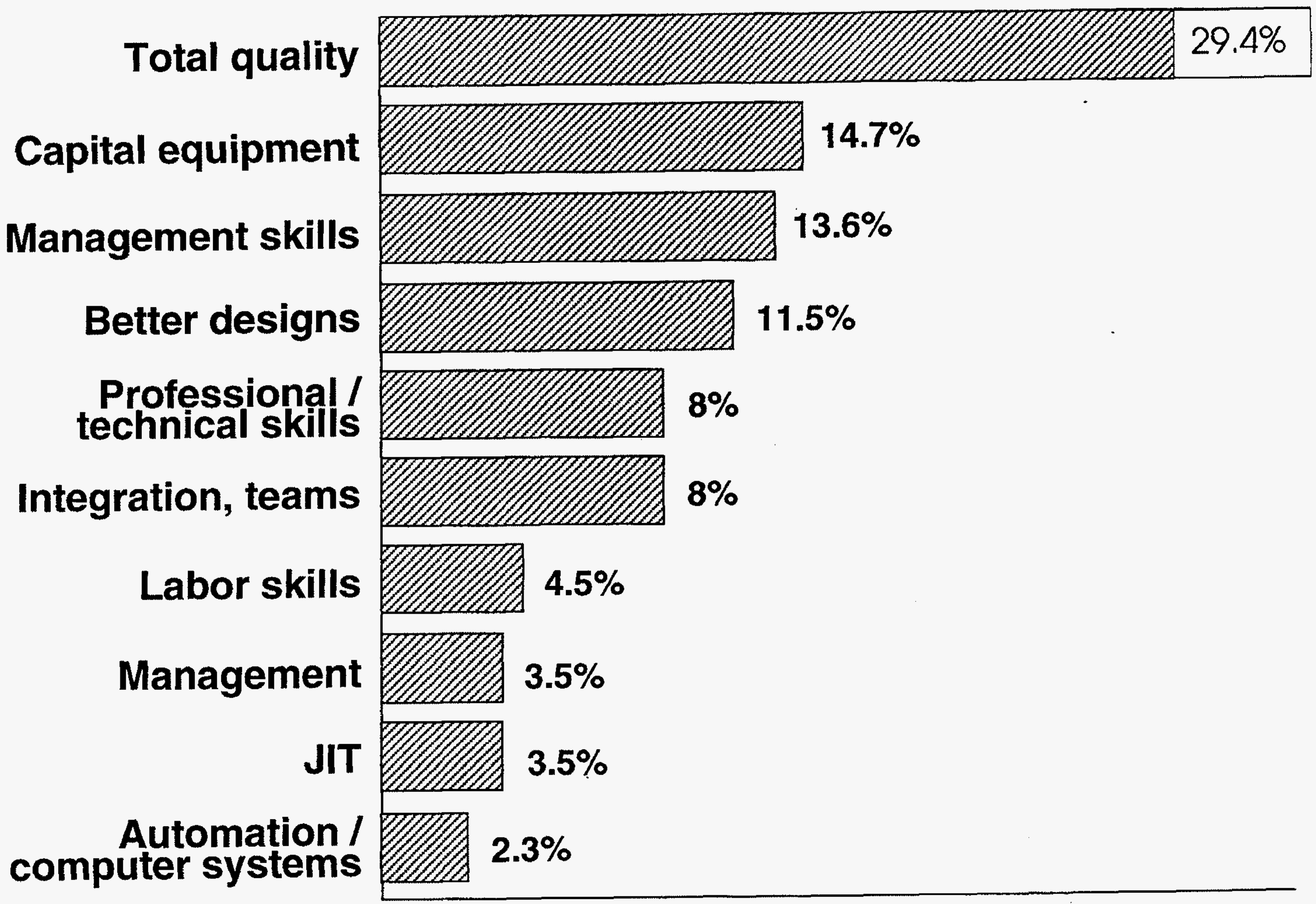


Figure 43. Investing to Meet Future Challenges [146]

C. The Emergence of a New Science Policy

The importance of understanding driven research as a critical factor in maintaining the Nations economic strength is reaffirmed by the House Science Committee, and the fundamental soundness of the Bush policy is validated. According to one study, publicly-funded research provided part or all of the foundation for 73 percent of the patents cited in the study. The public and private rates of return on the basic research investment are impressive. However, what is being discussed is a process that is one way in time; the feedback effect from later stages of the development process on basis research itself are not accounted for, and may be so complex that a determination of these effects is not possible. The principal conclusion of the committee was that the overall process is healthy and the goal of the House Committee's work was to "fine tune" the process to maintain and improve the health which required an inquiry into the workings of the process itself.

The report recognizes that the distinction drawn between "basic" and "applied" research by Dr. Bush are artificial distinctions, although budget line items are sometimes still organized today along these distinctions. It was brought out in testimony that the two motives of understanding and use can coexist in the same person, which can lead to creativity and productivity in the scientific enterprise. One witness testified that "a consistent virtue of U.S. basic research has been the pursuit of fundamental knowledge with a sharp eye for downstream applications." The DoD received the applause of the Committee for its success in funding research in this vein. Dr. Bush understood that the motives of understanding and use could coexist in the same person from the illustrious career of Louis Pasteur, but anyone who has worked in a large R&D organization with a wide spectrum of activities understands the inherent tension between basic and applied research during a budget squeeze that could have led Dr. Bush to observe: "applied research invariably drives out pure." Basic research is an easy target for budget cuts to solve short-term crises since the consequences of the reduction will not be felt in the short term.

D. MIMIC and VHSIC and the Linear Model

It is of interest to examine the formulation of VHISC and MIMIC in terms of two models of scientific research: The Bush linear model, and Pasteurs Quadrant. In the Bush "Linear Model," there is a one-way flow of activities in time from basic research to a useful product (Fig. 44), but the manner in which these activities are coupled together is left undefined. The motivation for basic research according to Bush was to increase "the general knowledge and understanding of nature and its laws," but basic research is conducted without "thought of practical ends," thus implying a conflict between basic and applied research. However, his observation that basic research is "the pacemaker of technological progress" implies some coupling mechanism undefined. How applied research, development, design, and manufacturing are coupled is also undefined as shown in Figures 46 and 47.

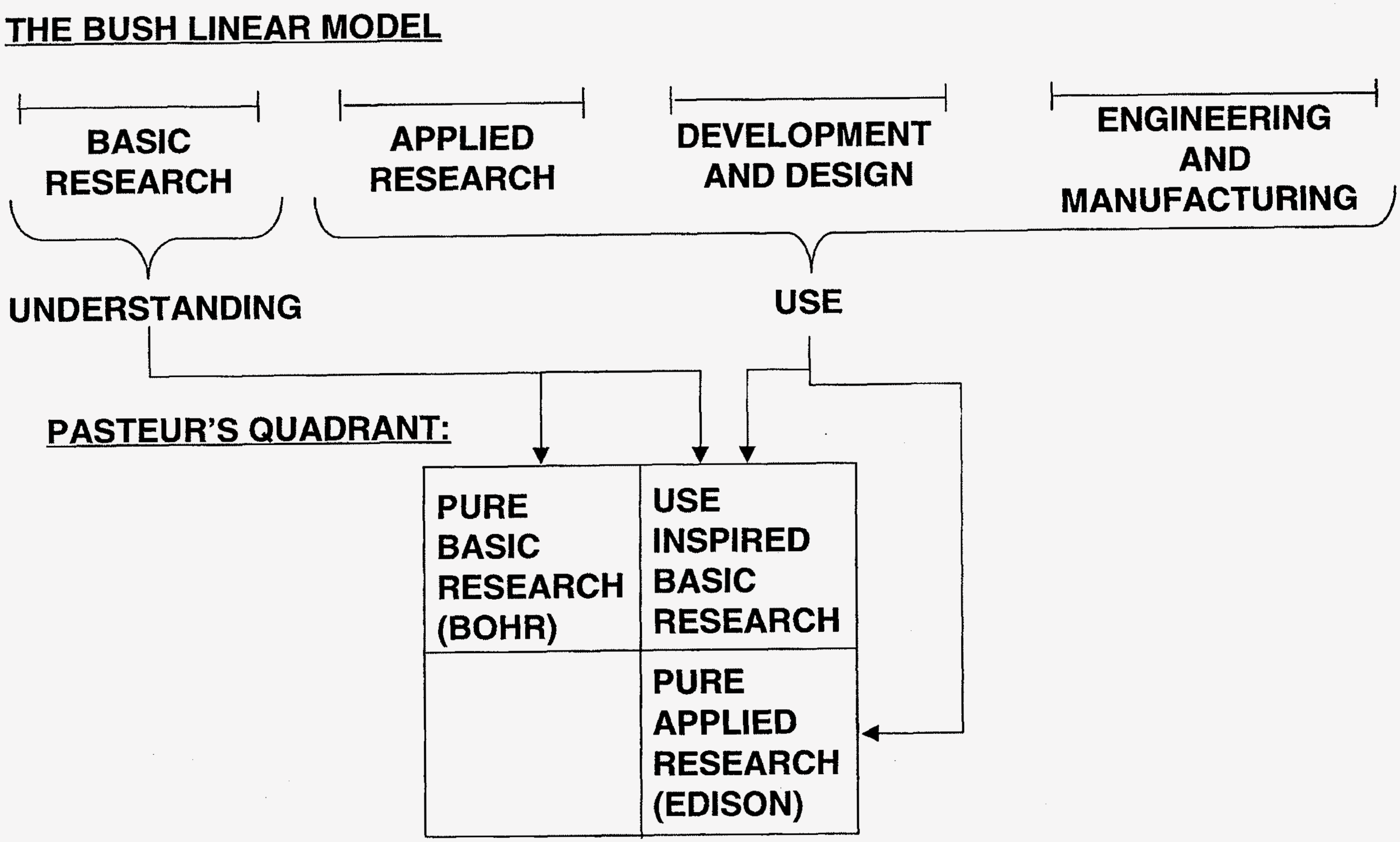


Figure 44. Comparison f the Bush Linear Model and Pasteur's Quandrant [2, 149]

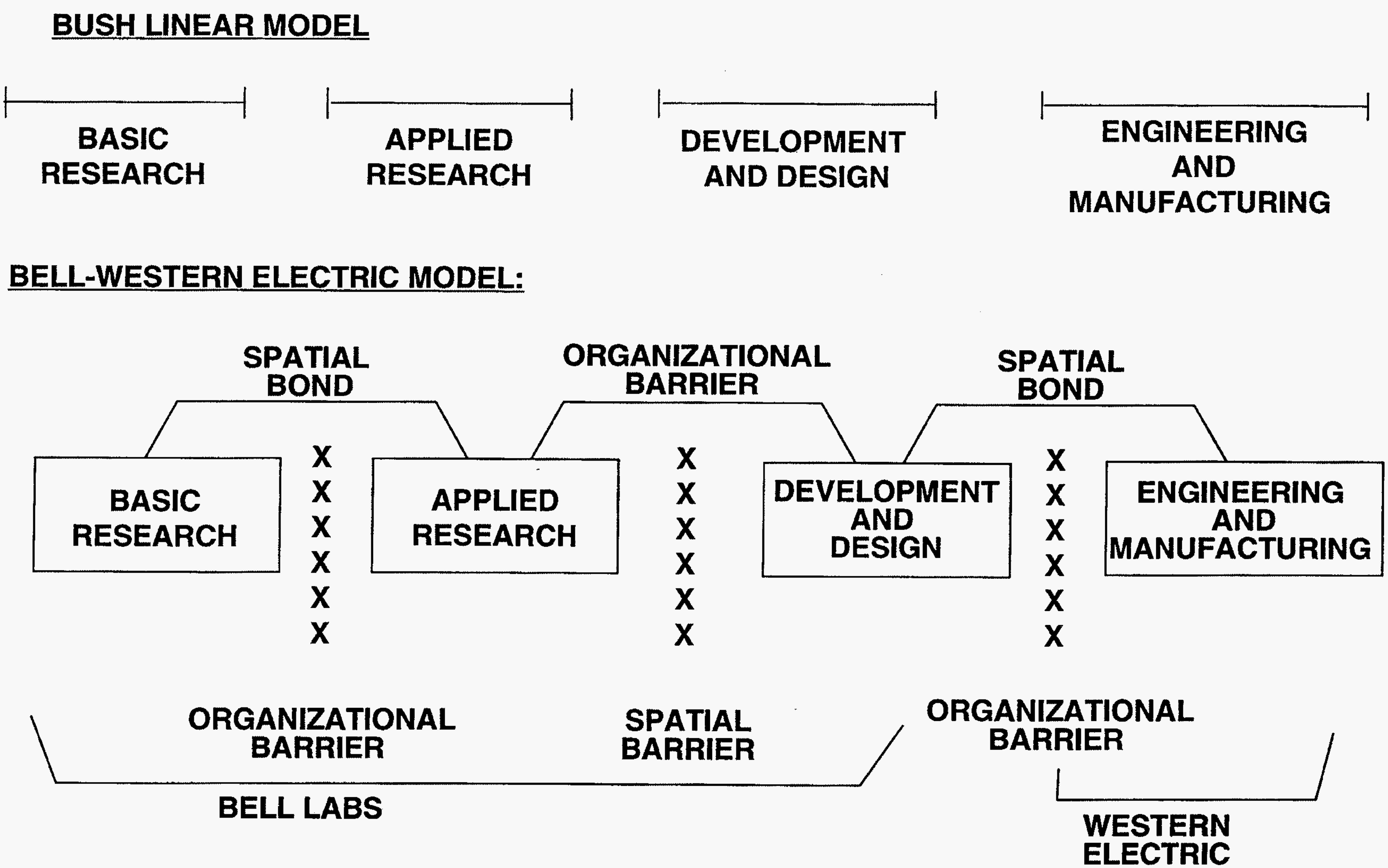


Figure 45. Comparison of the Bush Linear Model and the Bell-Western Electric Model [2, 149]

Although there is a long history of the institutionalized separation of pure and applied research, there is widespread recognition today that the one-dimensional flow of events in the Bush linear model does not correspond to reality. The one weakness of the model is that it does not account for the feedback effect that applied research may have in raising questions for basic research investigations. In fact, the motivation of both basic and applied research may reside in the same person, and this is reflected in the career of Louis Pasteur. To account for this, Stokes has reformulated the model of scientific research in two-dimensional form as shown in Figure 46, to allow the identification of use-inspired basic research in "Pasteur's Quadrant." [149]

An alternative model of the flow of events over the entire product cycle has been provided by Jack Morton, Vice President, Electronics Technology, Bell Telephone Laboratories. [150] This model may be interpreted as an information-processing network with feedback loops and forward information channels modulated by spatial and organizational bonds and barriers, as shown in Figure 45. For example, the organizational barrier between basic and applied research preserves the autonomy of the basic research group, but the spatial bond means that the two groups work in close physical proximity that encourages communications. Both an organizational barrier and spatial barrier separates applied research and development and design, which imply these functional areas are only loosely coupled. The organizational barrier between development and design, and engineering and manufacturing prevents crises in either area from disrupting operations in the other, but the spatial bond means that the Bell Labs development and design group was located in close physical proximity to the Western Electric engineering and manufacturing group.

The MIMIC and VHSIC programs were designed not only to couple the flow of events and feedback loops over the product cycle as illustrated in the Morton paper, but across multiple corporate boundries to produce and deploy multiple products in four application areas: radar, communications, smart weapons, countermeasures and counter-countermeasures. By framing the goals of the program in system terms, a coupling mechanism is established between the materials research, device design modeling, simulation testing, and system architecture that provides the motive force for innovation, that may take place not only at the basis research end of the process, but anywhere downstream as a result of the feedback process. The program formulation thus features the design of spatial and organization bonds and barriers and feedback loops across multiple corporate and government organizational barriers for multiple products in the four application areas cited. Both programs not only had clear application goals, but the goal of increased knowledge and understanding that places it in Pasteur's Quadrant. The structure of the program also provides a synergism that generates research questions for both Edison's quadrant and Bohr's quadrant.

Jack Morton has portrayed the evolutionary process of this model in Figure 45. In the first generation of electronic communication technology, macroscopic properties of a few materials to establish magnetic, electrical, insulating and mechanical properties of the materials for tube design and manufacture. Research in materials, devices, circuits, and systems were only loosely coupled. With the invention of the transistor, the breadth of knowledge in each of these categories increased as shown by overlap in the categories along the horizontal axis. Materials and devices were more tightly coupled as were circuits and systems. In addition, the intensity of knowledge increased as reflected by the growing height of the curves along the vertical axis. At the time Morton wrote his paper, the microcircuit revolution was just getting underway. The integrated circuit had been introduced in 1962, and the first steps had been made toward monolithic integration for both digital and analog applications in silicon and gallium arsenide. The first MEMS patent was issued in 1968, the year before publication of Morton's paper.

The microcircuit technology is no longer along one line as shown in Morton's chart, but has split into a series of microcircuit technologies with the evolutionary process described by Morton over 30 years ago continuing in each of them. The DARPA Microcircuit Technology Offices (MTO) manages the development of the microcircuit family under what DARPA defines as "our three core areas:" electronics, photonics and MEMS, as shown in Figure 46. The materials research areas are managed by the Defense Sciences Office (DSO), and the intimate coupling between materials research and device development is reflected in the fact that materials research projects can be found in both the MTO programs as well as the DSO programs. Eliot Cohen's analysis of the trends in active element phased arrays found eight cost drivers, all of which were sensitive to the quality of the starting material for this gallium arsenide-based technology (Fig. 47).

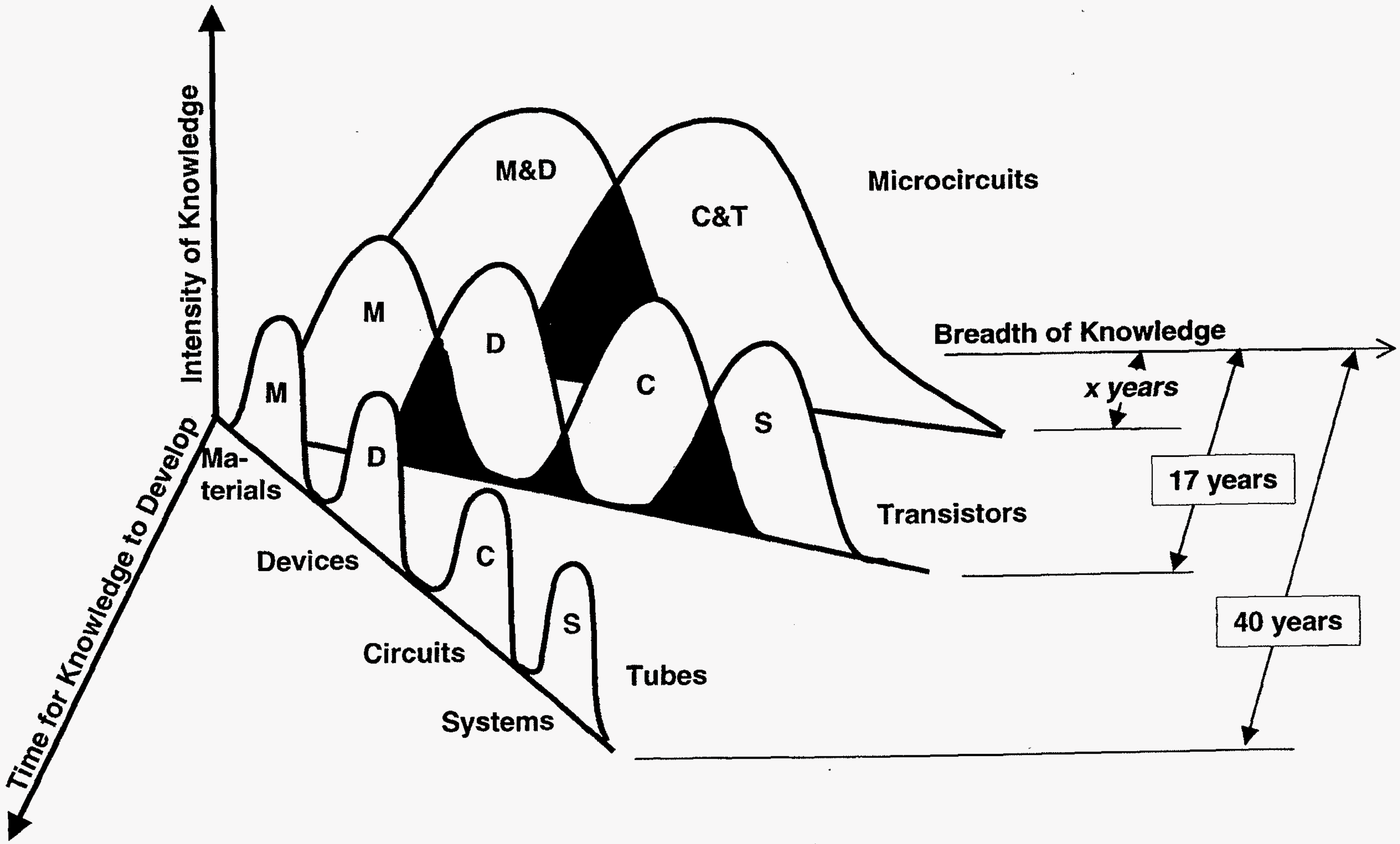


Figure 46. Speedup in Development of Knowledge as One Moves From One Technology Track to Another in Electronics: Knowledge Intensifies and Broadens [150]

- STARTING MATERIAL COSTS
- MATERIAL QUALIFICATION AND PREPARATION COSTS
- EFFECTIVE USE OF WAFER "REAL ESTATE"
- PROCESSING YIELD (LINE YIELD, DC YIELD, VISUAL YIELD)
- TEST (ON-WAFER AND POST PROCESSING)
- VISUAL INSPECTION
- PACKAGING
- FINAL TEST AND QA

Figure 47. Factors Impacting MIMIC Costs [136]

E. The Payoff of MIMIC

The program that began with the concern of the smart weapons community for the cost of millimeter wave missile seekers was completed in 1995, but was followed by an extension to the program called MAFET. [152] It was one of the most successful programs conducted by the DoD that established MIMIC as a robust dual-use technology with applications not only in smart weapons, electronic warfare, radar and communications, but in satellite communications, automobile anti-collision radars, wireless local area networks, and digital, cellular, and cordless phone services. As Defense Department budgets declined, the microwave industry was well positioned by the MIMIC investment to respond more effectively to DoD needs, as well as to the newly emerging commercial markets with the resultant benefit in the following application areas.

The maturation of MIMIC technology is already having a profound effect on smart weapons development. The Aviation and Missile Research, Development, and Engineering Center (AMRDEC) formed a key technology thrust in Precision Guidance of Small Diameter Weapons in response to the revision in 1993 of FM-100-5 OPERATIONS in order to better match the mission capability of the Center to the needed capability of the Army for fighting and peace keeping in the information age. For small diameter missiles with RF data links, MIMIC offers the potential for better integration of the missile-borne power amplifiers with the missile antennas to achieve much-needed efficiency in missile systems. One of the most pervasive enabling technologies for advancing the art of precision guidance of small diameter weapons is Microelectromechanical Systems (MEMS), and since both MEMS and MIMIC have common origins in microelectronics, it can be expected that the merging of the two technologies will be an important factor in achieving the goals of precision guidance of small diameter weapons. MIMIC and MEMS technology will allow the packaging of millimeter wave homing seekers in smaller diameter missiles. For missiles too small to feature a homing seeker, MIMIC sources integrated with symmetrically configured end-fire arrays may offer an alternative.

Another key technology thrust is multispectral missile seekers. The MIMIC now offers a mature front-end millimeter-sensing alternative that may be combined with other millimeter or infrared wave bands. As an example, in 1993 the BAT Project Office began a P3I effort to upgrade the homing seeker to engage additional targets and improve performance in adverse weather. The millimeter portion of this millimeter-infrared seeker will be able to capitalize on the advances in MIMIC technology that were achieved after the work on the MLRS-TGW seeker under Manufacturing Methods and Technology programs.

The MIMIC program offered a more economical sensing option for millimeter wave seekers but shrinking budgets and the downsizing environment provided further stimulus for the development of the concepts of flexible manufacturing in such programs as the DARPA-Tri-Service Affordable Multi-Missile Manufacturing (AM3). This Advanced Technology Demonstration effort has the objective of reducing the production cost of ongoing missile programs by 25 percent, the development and production cost of new missiles and upgrades by 50 percent, and the reduction of the development cycle time by 50 percent. [151] The principal focus of the program is on missile seekers and guidance and control sections which represents more than 60 percent of the missile unit production cost.

Monolithic design of high-speed photo detectors and photo-emitters on semi-insulating gallium arsenide provided the foundation for coupling fiber-optic communication and information processing, and the progress in MIMIC technology enhanced the potential for coupling the areas of lightwave and millimeter and microwave technologies. Peter Herczfeld served as guest editor of the May 1990 issue of the Joint IEEE Transactions on Microwave Theory and Techniques, and the Journal of Lightwave Technology that contained 50 papers in this area organized in two categories: (1) distribution of microwave and millimeter wave analog signals, and (2) optically controlled devices and circuits. [152] In the first category, work at the AMCOM RDEC, has provided a means for using multispectral seekers on a fiber optic guided missile by independently transmitting millimeter and infrared sensor imagery over the fiber optic link to a ground control station. [153] In the second category, photonics and millimeter wave technology have been integrated into a millimeter wave transmit-receive module that can provide the basis for either a radar or communication relay. [154] In 1992, Herczfeld proposed microwave-photonics integrated circuits as a follow-up to MIMIC. [155] In a statement before the Subcommittee on Emerging Threats and Capabilities Committee of the Senate Armed Services Committee, Dr. Frank Fernandez reported that the goal of the Radio-Frequency Lightwave Integrated Circuits program (R-FLICS) was "to product photonics technology that will enable development of high-performance radio frequency circuits that can route, control, and process analog radio frequency signals in very broad, but militarily crucial range of .5 to 50 gigahertz." [156]

The conduct of the MIMIC program provided a valuable model in public and private sector cooperation in achieving broad national objectives. Although the MIMIC program had its origins in the concern of one segment of the defense community for the cost of its products (smart weapons), there was also recognition in the technical community that the technology had broad applicability in commercial applications such as automobile radar, direct-broadcast TV, and wireless communications that could be traced back to the emergence of microwave monolithic integrated circuits. The automobile electronics market is being pursued not only by American automobile manufacturers, but a host of Japanese and German firms as well. MIMIC is a key technology in enabling the direct broadcast television industry to meet not only the technical challenges, but remain competitive in a rapidly expanding market. But direct broadcast satellites provided only one part of the communication revolution to which MIMIC is making a contribution: Satellite links with the capability to provide video conferencing, voice, data fax and two-way paging are already providing services in a rapidly expanding market.

Would MIMIC have happened anyway without the stimulus of the DoD program? There is absolutely no support for this. In 1985, the year DoD made the decision to start the MIMIC program, it was recognized that the U.S. would be confronting the Japanese in head-to-head competition in gallium arsenide technology, as well as in silicon technology. The U.S. leadership in the semiconductor market was already in sharp decline including the loss in market share of U.S. semiconductor equipment and materials suppliers, such as lithography equipment, etching systems, deposition systems, and semiconductor materials, and others. In addition to other systemic problems in the industry including the cost of capital to U.S. suppliers as

compared to that in Japan, the working relationships between U.S. suppliers and the U.S. semiconductor manufacturers was poor in contrast with these relationships in Japanese industry.

Since this loss in leadership was in the relatively mature silicon technology, it is hardly reasonable to expect that the U.S. could have achieved a position of leadership in the relatively immature gallium arsenide technology without the stimulus of the DoD program.

XIII. THE ELEMENTS OF A SUCCESSFUL PROGRAM

A. Introduction

The MIMIC program was formulated in the decade when the U.S. was reeling from the blows of foreign competitors. In 1986, the year before the MIMIC program was launched, the U.S. suffered the first high technology trade deficit. Approximately half of all patents awarded were going to foreign inventors. That same year, W. Edwards Deming presented a plan for the transformation of American industry based on his 14 points [167] and Genichi Taguchi introduced a new concept of quality engineering based on the loss function [168]. There was growing recognition of the need to reexamine the framework for the Federal Government is support of science and technology derived from the Vannevar Bush report, "Science, The Endless Frontier," 1945, which advanced the thesis that support of basic research, the principal fountainhead of innovation, was a proper role of the Federal Government, and the more applied areas were left to industry. The principal Federal Government investment areas for basic research were defense and health, which left a policy void in the area of research leading to the commercialization of technology. The consequence of this policy accorded low status to manufacturing technology and left the U.S. vulnerable to foreign competition. According to the report by the Council of Productivity, this Post World War II research-driven model of the innovative process:

> "Viewed innovation as a linear process - - starting with a major scientific breakthrough, progressing through design, development and production, and ending with marketplace distribution. Consequently, the model emphasized basic research. The research-based model must be supplemented by another view that focuses on market-driven applications of the technology." [3]

The success of the MIMIC program can be attributed to the strong leadership of the DoD and service directors of the program and their many top associates in Government, industry, and academia, who not only possessed an intimate knowledge of the technology, but the managerial agility to navigate in an era of national soul-searching and provide the following characteristics of the program.

B. Unprecedented Atmosphere of Cooperation

The leadership of the MIMIC program recognized that if the microwave industry was to produce millimeter and microwave monolithic integrated circuits with acceptable costs for defense applications, it would also have to provide the foundation for profitable manufacturing to allow the industry to compete with volume production in the global marketplace. To achieve this goal, Cohen identified four tasks the industry teams would have to achieve: (1) Robust and controllable processing capabilities to allow chip fabrication with high yield, (2) Highly automated on-wafer testing to characterize and screen chips early in the fabrication process, (3) Comprehensive computer-aided design system with an open architecture framework, and (4) Invoking modern production discipline in all the design, fabrication, assembly, and test procedures in order to transform them into sustainable, low-cost production operations. [141]

Achievement of the program goals required that the national interest take precedence over the interest of the individual companies. Cohen observed that:

> "If these tasks are to be accomplished efficiently an unprecedented degree of cooperation must take place between the many companies engaged in the program. The cooperation must extend over all the various technical disciplines that contribute to the design, fabrication, and use of microwave and millimeter wave hardware. The MIMIC program was specifically structured to foster and manage such interactions." [141]

As a result of this guidance, the barriers to the free flow of information were removed within the teams and between the teams. Problems common to the industry in the areas of Computer-Aided Design (CAD), interfaces, and modeling received special attention in the collective efforts, thus allowing a higher productivity of research and development investments. As part of this cooperative effort, the Raytheon-TI team and the ITT-Martin-Marietta team formed joint ventures to achieve program goals with significant savings of time and money.

C. The Framework for Continuous Improvement

W. Edwards Deming conceived his 14 points as the basis for transforming industry into organizations producing quality products at lower cost in shorter cycle times through a process of "continuous improvement." Continuous improvement in the Deming Model is concerned with reducing the variations in manufacturing the process about some target value. [167] The MIMIC technology offered a broad array of target values for metrics that managers utilized to provide the framework for continuous improvement. E.D. Maynard provided the guidance for establishing more detailed metrics for some of the advantages offered by MIMIC: (1) reduction in size and weight (10:100:), (2) improvement in reliability (100:1), (3) reduction in parts count (30:1), and (4) lower life cycle cost (10:1). [118] The program was also framed in such a way that metrics for improvements within both Phase I and Phase II could be established for yield, cost and power added efficiency for power amplifiers. [135] In some instances, according to Cohen, retrofit of MIMIC hardware into existing modules and subsystems had the

purpose of reducing cost and improving reproducibility, reliability, and performance, although generally a retrofit in an existing system did not result in space savings or significant improvement in performance. For future systems, MIMIC offered two advantages: (1) increasing functionality within reduced space requirements with advantages of reduced cost and improved reliability, and (2) enlarging the opportunity to design and produce systems not achievable in the older technologies. The opportunities for improvements in existing and planned systems in 1991 were presented in Reference 134.

The potential advantages offered by MIMIC for phased array radars in terms of reduced cost, size, weight, and improved reliability and power-added efficiency were recognized in the mid 1960s, and the transmit-receive module was the focus of concentrated effort from the beginning of the MIMIC program. At the 1996 IEEE International Symposium on Phased Army Radars, Cohen reported that an order of magnitude reduction in GaAs MIMICs cost had been achieved since 1988, by focusing on both the nonrecurring and eight recurring cost factors: starting material cost; material qualification and preparation; effective use of wafer real estate; processing yield; testing; visual inspection; packaging; final test; and quality assurance. [136]

Nonrecurring cost reduction was the focus of a major effort under the Microwave Analog Front End Technology Program (MAFET) to introduce virtual prototyping in the first cycle of design-build-test, and reduce the number follow-on cycles from 3 or 4 to 2. A major program goal in the High-Density Microwave Packaging Program was to reduce the T/R module cost by an order of magnitude or more at required performance levels with lower weight and cost in a given form factor. [155]

D. Focusing on the Entire Product Development Cycle

The declining U.S. competitiveness in the late 1970s and early 1980s provided the motivation for a number of studies that concluded that the major barrier to U.S. leadership was not external factors, but was within the corporations themselves. Bernard Slade explored this question with 21 professors and 200 senior executives .[146] Most of the academics attributed the decline in U.S. competitiveness to weakness in manufacturing, and 40.6 percent of the senior executives identified integrated design teams as the factor needed for shortening the product development cycle. Slade attributed the problems of U.S. industry to the failure to adapt to technological change from the 1950s when the product cycle was much shorter than it is today; risk were lower, and the product cycle was determined primarily by what happened on the factory floor; since the communication process between the design engineer and the manufacturer was a straightforward process. The arrival of high technology and the impact on manufacturing brought about disruptive change that made U.S. vulnerable in global markets. Part of the solution has been to provide for intensive management of technology development in a separate S&T organization to 'mature' the technology to a high readiness level before handoff to a product or program development organization. General Accounting Office studies have found that application of this process improves the probability of success for both commercial and military programs, but it is more difficult to provide the incentives to operate with this model in Government than in industry where the motivation is built in.

The findings of the Slade study were consistent with the conclusions of studies by the National Research Council. In one National Research Council Study it was found that:

> "Effective design and manufacturing, both necessary to produce high quality products, are closely related. However, effective design is a prerequisite for effective manufacturing; quality cannot be manufactured or tested into a product, it must be designed in. Unfortunately, the overall quality of engineering design in the United States is poor." [157]

In another study, the National Research Council found:

> "Progress in U.S. manufacturing technologies and competitiveness faces significant barriers: inflexible organizations; inadequate technology; inappropriate performance measures; and lack of appreciation for the importance of manufacturing. These barriers are addressed in this report of the Committee on Analysis of Research Directions and Needs in U.S. Manufacturing, Manufacturing Studies Board, Commission of Engineering and Technical Systems, National Research Council. The report identifies and analyzes research needs in five critical areas of manufacturing: intelligent manufacturing control, equipment reliability and maintenance, advanced-engineered materials, manufacturing skills improvement, and the product realization process." [158]

The product realization process must match the product development, deployment, and support to market requirements. The MIMIC program placed strong emphasis on the product realization process:

> "MIMIC contractors are required to prepare a business plan which is updated on a regular basis and includes a comprehensive market analysis for MIMIC products, an assessment of which MIMICs are needed for insertion into military subsystems, plans for effecting these insertions with the lowest possible risks, cost analyses and approaches to making MIMIC chips/modules available to all other prospective DoD buyers. Each contractor must also establish an additional independent source of supply for the chips that it manufactures." [140]

A vision of a new industrial America incorporating the changes in the product realization process is presented in Reference 159.

E. A Model for Concurrent Engineering or the Integrated Product-Process Development Concept

The weakest link in the product development cycle grew with the impact of high technology on manufacturing; the recognition grew that management had to confront three issues that have a major impact on the length of the product cycle. According to Slade these three issues are: (1) How to make the product concept and performance specifications responsive to the market and customer needs, (2) How to know when and how to decide among several possible design alternatives, and (3) How to determine the magnitude of the technical and performance advances that can be achieved with technical risk. [146]

In recognition of these changes in strategic vision in industry, DARPA sponsored a Workshop on concurrent engineering, in 1987. A Follow-up study was performed by the Institute for Defense Analysis (IDA) entitled The Role of Concurrent Engineering in Weapon System Acquisition, December 1988. [160] In the IDA study of concurrent engineering in 11 firms, it was shown that substantial reduction in cost and product cycle time could be achieved. The basic idea is that R&D and manufacturing process development are worked on concurrently. The definition of concurrent engineering by Winner, et al. in the IDA study suggested that shortening the product cycle involved more than improving the linkage between design and manufacturing through the issues cited by Slade:

> "Concurrent engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements." [160]

In the formulation of the MIMIC program, there was recognition that incorporating these principles could serve as a catalyst in bringing about needed change. The industrial base analysis conducted in the early 1980s prior to the formulation of the MIMIC program, had found that there were 40 firms with IR&D programs in microwave and millimeter integrated circuits, but manufacturing process development work was nearly nonexistent as formal programs. The background papers and memoranda developed by the military services and DoD recognized that the MIMIC program could not be just "more of the same" of what industry was already doing. The MIMIC program would have to be a structured program formulated and executed by interdisciplinary teams, with a strong component of manufacturing process development in the foundation of the program. The requirement for the teams to develop business plans encouraged the teams to view the product development cycle from fundamental research to the customer.

MIMIC contractors were required to prepare a business plan which is updated on a regular basis and includes a comprehensive market analysis for MIMIC products, an assessment of which MIMICs are needed for insertion into military subsystems, plans for effecting these insertions with the lowest possible risks, cost analyses and approaches to making MIMIC chips/modules available to all other prospective DoD buyers. Each contractor must also establish an additional independent source of supply for the chips that it manufactures.

F. Lessons Learned From the Very High Speed Integrated Circuits Program

The formal structure of the MIMIC program was similar to that of the VHSIC program and featured the concept of strong DoD management with service program directors to draw on in-house and industry resources in a coordinated manner for program planning and execution. The focus of VHSIC was on digital systems and was based on a relatively mature base in silicon, while MIMIC was to advance microwave and millimeter analog technology based on the more intractable material of gallium arsenide. The two technologies were viewed as having a complementary role for defense applications. According to Maynard, who directed both programs:

> "The MIMIC program will provide advantages to the 'eyes and ears' of systems similar to the 'brains' by VHSIC, advantages in performance, size, weight, cost, power and reliability." [90]

However, VHSIC and MIMIC were distinctly different in the level of maturity of the two technologies. At the time the VHSIC program was initiated, DoD was a customer for less than 10 percent of the silicon microelectronics market, so it was becoming difficult to get the attention of industry for defense applications. DoD was concerned about the long lead time between advancements in the technology and the introduction of these advancements in weapon systems. The VHSIC response to this problem was a two-phase program that included bipolar, NMOS, and CMOS technology. Under Phase I, the objective was chips with 50,000 gates with 1.25 micron size and 25 Mhz clock rates. The VHSIC Phase I program objective was to speed up the insertion of Very Large Scale Integrated (VLSI) circuits into military systems. [120] Under Phase II, the objective was chips with 100,000 gates with .5 micron size with clock rates of 50 Mhz or higher. At the close of Phase II, the goal was to reduce the delay between commercial 1990 VLSI technology and military insertion to two years. On the other hand, when the MIMIC program was initiated, DoD was the principal customer for the technology, but there was widespread recognition of the potential of the technology for commercial application and realizing this potential was implicit in the MIMIC program goals.

The VHSIC program was not just about producing high-speed chips for military systems, but included a comprehensive program in equipment development, manufacturing processes, and testing technology that provided a more mature manufacturing technology base for MIMIC. Both programs focused on the design environment with the emphasis on hardware description languages to provide for easy interchange of models and designs, tool integration, and tool interoperability. However, although the analog CAD market has been growing well since the completion of MAFET in 1995, it represented only about 10 percent of the CAD market in 1996, the year MAFET was initiated. [160, 161] The MAFET program provided an effective stimulus in the development of microwave and millimeter wave analog design tools. [160]

A very important lesson from the VHSIC-MIMIC experience is that the health of the semiconductor industry in global commercial markets is an essential foundation for also meeting defense needs. High-volume production is essential for the health of the semiconductor industry, but this is provided by commercial markets, not military markets. However, semiconductors also provide the most powerful leverage in achieving technological superiority in weapon systems,

but this cannot be achieved with an ailing industry. This logic was the principle theme of the report of the Defense Science Board Task Force "Defense Semiconductor Dependency." [122] This inextricable linkage between defense and commercial interest was acknowledged by Caposell:

> "The MIMIC program benefited from lessons learned during the VHSIC effort. VHSIC was successful in moving digital INTEGRATED CIRCUITS technology forward at an accelerated pace; however many of the VHSIC foundries did not succeed after the conclusion of the program largely because of a lack of orders for VHSIC parts. This resulted in part, from the VHSIC program guidance that emphasized generic chips for which it turned out, there was almost no market. Fortunately, the strong commercial interest in the technology quickly provided a home for VHSIC, mostly in the form of application specific ICs and memory chips." [135]

G. Integration of Metrology and Standards with Technology Development

1. Air Force GaAs Material/Device Correlation Study

Starting material quality held the key to the success of the MIMIC program. Cohen identified eight factors impacting recurring costs, and materials quality impacts each of the eight. [136] A well-timed research effort was initiated by the Air Force Materials Laboratory in fall of 1983, three years before the Phase 0 MIMIC BAA was issued with the objective of improving the quality of undoped semi-insulating liquid encapsulated Czochralski GaAs material. [162] One contract was awarded to Texas Instruments Central Research Laboratory for low-pressure growth, and a second contract was awarded to Rockwell International Aeroelectronics Research and Development Center for high-pressure growth. Deliverables under the program were test boules of minimum length and diameter sliced into 40 wafers and prepared for further analysis and device processing.

The second step in the program was undertaken in 1984, when the wafers were distributed under four contracts to Raytheon Research Division, Texas Instruments incorporated, Hughes Aircraft Company, and Raytheon, for evaluation and processing of five wafers from a boule into several semiconductor devices followed by documentation of materials, processing, and device measurements. The test data from the program was collected by the Microwave Technology Branch, and the computer program WAFER was developed in conjunction for this effort. [163]

Although the program was based on mature device technology, an immediate finding was that numerous variations in wafer processing and device testing procedures made it difficult to establish an unambiguous relationship between material quality and device performance, and underscored the importance of some form of standardization for basic materials-type classification. [164]

2. National Bureau of Standards

A most fortunate circumstance was the participation of the NBS in formative stages of the MIMIC program. The principal concern when the market for MIMIC was primarily military was that the absence of calibration standards during weapon development and acquisition would leave the Government at the mercy of contractors for system performance test and evaluation. In 1986, Brian Belanger, of NBS, conducted a review of DoD directives, instructions, and MIL standards and measurement requirements and came to the conclusion that there were no formal DoD regulations or directives explicitly requiring those managing various aspects of the program to consider and address measurement standards requirements. NBS began immediately (1986) formulating a program on metrology and standards that would be integral to the development and application of MIMIC technology with the primary focus on military applications.

The growing awareness of the weak Federal role in research for commercialization of technology led to the 1988 Omnibus Competitiveness and Trade Act that transformed NBS into the NIST with enlarged responsibilities in this area. The following year, the first annual MIMIC conference was held at Gaithersburg, MD with NIST serving as host. As the MIMIC program unfolded, the customer base for the technology shifted from military applications to commercial wireless applications, and formal link between U.S. competitiveness and metrology and standards as a key element in global strategy was recognized in the National Technology Transfer and Advancement Act of 1995, the year the MIMIC program ended.

H. MIMIC: A Dual-Use Technology

The Defense Science Board Study concluded that the health of the semiconductor industry was inextricably linked with the development of advanced semiconductor devices for defense applications. The health of the industry was dependent on a high-volume commercial market, but the semiconductor device was a key component in advanced weapon design, and the required numbers were relatively small for this application. A major goal of acquisition reform was to unify the defense and commercial industrial bases so that defense needs could be met, and the health of the industry maintained in global markets. [165] The DoD identified three pillars of the dual-use technology policy: (1) investment in R&D on dual-use technologies, (2) integration of military and commercial production, and (3) insertion of commercial capabilities into military systems.

The MIMIC program was a key dual-use technology that was initiated when the market for the technology was principally military. Since so few MIMIC devices were required for defense, the prices were high, therefore part of the dual-use strategy was to encourage the industry to seek commercial applications for analogous defense devices or subsystems so defense needs could be met at lower prices. One example cited on the application of this strategy was the Air Force phased array radar that used 2000 MIMIC TR modules with an original cost of $8,000 each. By reducing the time and cost of the front-end design process, the cost of the TR modules was reduced to about $2,000, but DoD supported efforts to apply the technology in collision avoidance systems, for automobiles, wireless communication, and air traffic control signal processing.

The development of a family of radars under the Modular Airborne Radar (MODAR) program by the Westinghouse Electronic Systems Group for both the commercial and military aviation markets provides another model of the application of MIMIC in the dual-use concept. The application of the family of radars was for detection of wind shear in time for the aircraft to avoid the hazard. The MODAR integrated product-process development team included the MIMIC designer, power amplifier designer, transmitter designer, manufacturing engineering, and test engineer. The team conducted careful trades of various transmitter power source architectures including IMPATTs, TWTs, and MESFET amplifiers. The MESFET power amplifier was selected as the building block for the transmitter. Achieving the cost and performance goals required an intensive effort to identify the materials, processing, and testing cost. The process led to a successful design that was applied in MODAR-3000 for the commercial market and the MODAR-4000 for the military tanker/transport market. [164] According to the Defense Science Board Study: "The results of the MODAR program were quite startling. The product development cycle for a new prototype was reduced by more than 50 percent (from 12 months to 5 months). The prototype development cost was also reduced by 50 percent. Hardware integration and harmonization took two weeks instead of eight. The radar worked and performed all of its basic functions in its first flight test 22 weeks after program start." [166]

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ACRONYMS

AM3	Affordable Multi-Missile Manufacturing
AMC	Army Materiel Command
ARDEC	Armaments Research, Development, and Engineering Center
BRL	Ballistic Research Laboratories
CAD	Computer Aided Design
CCG	Calibration Coordination Group
CMOS	Complimentary Metal Oxide Semiconductor
DARPA	Defense Advanced Research Project Agency
DDR&E	Director of Defense for Research and Engineering
DOD	Department of Defense
DOFL	Diamond Ordnance Fuze Laboratory
DSARC	Defense Systems Acquisition Review Council
DSO	Defense Sciences Office
ECL	Electronics Components Laboratory
ET&DL	Electronics Technology and Devices Laboratory
FET	Field Effect Transistor
FM-CW	Frequency Modulated-Continuous Wave
GAO	General Accounting Office
GE	General Electric
HBT	Hetrojunction Bipolar Transmitter
HEMT	High Electron Mobility Transistor
IDA	Institute for Defense Analysis
IPPD	Integrated Product and Process Development
IR&D	Independent Research and Development
IRE	Institute of Radio Engineers
M^3I	Monolithic Millimeter and Microwave Initiative
MAFET	Microwave Analog Front End Technology Program
MANTECH	Manufacturing Technology
MEMS	Microelectromechanical Systems
MERA	Molecular Electronics for Radar Applications
MIC	Microwave Integrated Circuits
MICOM	US Army Missile Command
MIMIC	Microwave and Millimeter Monolithic Integrated Circuits
MLRS-TGSM	Multiple-Launch Rocket System-Terminally Guided Submunition
MM&T	Manufacturing Methods and Technology
MOA	Memorandum of Agreement
MODAR	Modular Airborne Radar
MOFA	Multi-Option Fuze for Artillery
MRSS	Microwave Radiometer Seeker Subsystem
MTO	Microcircuit Technology Office
NBS	National Bureau of Standards
NIST	National Institute of Standards and Technology
NMOS	N-Metal Oxide Semiconductor
PEMA	Procurement of Equipment and Missiles, Army

ACRONYMS (CONT)

PEP	Producibility Engineering Planning
PESO	Product Engineering Service Office
PNMS	Promote National Measurements Standards
R&AT	Research and Advanced Technology
RDB	Research and Development Board
RDT&E	Research, Development, Test, and Engineering
RF	Radio Frequency
SADARM	Search and Destroy Armor
SCEL	Signal Corps Engineering Laboratories
SCORE	Signal Communication via Orbiting Relay Equipment
SEMATECH	Semiconductor Manufacturing Technology
SMDO	Space and Missile Defense Organization
TEM	Transverse Electromagnetic Mode
TGSM	Terminally Guided Submunition
TGW	Terminally Guided Warhead
TR	Transmit/Receive
TRADOC	US Army Training and Doctrine Command
TWT	Traveling Wave Tube
URSI	International Scientific Radio Union
US	United States
USDRE	Under Secretary of Defense for Research and Development
VHSIC	Very High Speed Integrated Circuit
VLSI	Very Large Scale Integrated

APPENDIX A
MILESTONES LEADING TO THE DEPARTMENT OF DEFENSE MICROWAVE AND MILLIMETER MONOLITHIC INTEGRATED CIRCUIT PROGRAM

Thanks are due Dr. Robert Heaston, Staff Specialist, Office of the Under Secretary of Defense (IR&AT), and Director, Guidance and Control Information Analysis Center, and Mr. Jerry Dickson, electronics engineer, Systems Engineering and Production Directorate, RDEC, AMCOM, for their contribution to this section of the report.

MILESTONES IN THE EVOLUTION OF THE DEPARTMENT OF DEFENSE MICROWAVE AND MILLIMETER WAVE MONOLITHIC INTEGRATED CIRCUIT PROGRAM

INTRODUCTION

The Department of Defense (DOD) Microwave and Millimeter Wave Monolithic Integrated Circuit (MIMIC) Program conducted in the 1980s and 1990s, was the culmination of advances in materials research, physics of semiconductor devices, transmission media, modeling and simulation, device development, manufacturing process development with roots in research conducted prior to and during World War II. A primary objective was to achieve compact, low-cost, and highly reliable millimeter and microwave circuit functions that could withstand extreme environments in weapon systems. The program provided a unique architecture in which program goals were framed in system terms to provide the linking mechanism between materials research, device design, modeling, simulation, and testing leading to applications in four major areas of high technology; radar, communications, countermeasures - counter-countermeasures, and smart weapons. Economy was achieved by fabricating both the active and passive circuit functions and inter-connections in monolithic form in semi-insulating gallium arsenide wafers.

When the program was being formulated in 1986 the market was principally military, but when it ended in 1995, the market was primarily commercial. The success of the program makes it a useful model for the design of other programs to achieve national objectives, for defense or competitiveness in international markets. The objective of this report is to summarize the milestones leading to the formulation and execution of the program.

Two key technologies that provided the foundation for radio proximity fuze program in World War II were miniature vacuum tubes for hearing aids that had to be ruggedized for application in bombs, missiles and projectiles, and printed wiring technology that not only could be adapted for making the electrical connections to the circuit elements in an automated process, but the fabrication of the passive circuit elements including resistors, inductors, and capacitors. At the close of World War II, in anticipation of commercial applications of the technology , the National Bureau of Standards published a comprehensive technical report on printed wiring technology as well as the 1948 IRE journal article on printed circuit technique. The transistor quickly replaced the miniature tubes in radio circuits, and the emergence of low cost transmission

media allowed the first planar fabrication of microwave printed circuits in the early 1950s that could be conceived of at several levels of "integration" hence the term microwave integrated circuits or more correctly "hybrid integrated circuits" since they are not fabricated in monolithic form.

In a program as complex and extending over such a long period of time, no two observers would be likely to select the same list of milestones for the program. This list represents the author's view that favors milestones in the Army contributions to the MIMIC program since the author had a better knowledge of the Army efforts than those of the other services. If the contributions of the other services and industrial and university sectors have been slighted on the list, it can be attributed to the authors ignorance. Heavy reliance has been placed on open source publications such as the Microwave Journal, IEEE Transactions on Microwave Theory and Techniques, Journal of Electronic Defense, Symposium Proceedings, and unpublished papers briefing, correspondence and memoranda concerned with program formulation and execution. In addition, Dr. Robert Heaston, a member of the office of Undersecretary of Defense for Research and Engineering kept a log of several of the key decision milestones that have been included in this report.

The milestones presented includes a mixture of scientific and technical as well as programmatic milestones. No attempt has been made to capture a comprehensive treatment of all the methods of printing circuits some of which had origins in U.S. British and German Work in the 1930s. The methods employed up to the time the Brunetti - Curtis paper was published in 1948 included painting, spraying, and die-stamping. The principal advantages of printed circuits included uniformity of production, reduction assembly and inspection time, cost, live rejects, and purchasing and stocking problems.

Also, no attempt is made to present all the device and process developments in genesis of the transistor. The key active device in the formulation of the MIMIC program was the Metal Semiconductor Field Effect Transistor (MESFET). William Shockley had investigated and made a record of a field effect transistor before World War II, but it was decades later after a better understanding of the physics, and advances fabrication the the first gallium arsenide field effect transistor was fabricated, and reported by C.A. Meade, in "Schottky-Barrier Field Effect Transistor", Proc. IRE Letters Vol 54, pp-307-308, February 1966.

The Research, Development, Engineering and Missile Systems Laboratory (RDE&MSL) had a pivotal role in the formulation of the MIMIC program that was based on a cordial working relationship with the Electronics Technology and Devices Laboratory who provided the technology base in millimeter wave technology in response to the smart munitions requirements from RDE&MSL. It was the technical and cost data derived from the MICOM Mantech program on millimeter wave seekers and other MICOM industrial base analysis and the work of the DOD M^3I committee that led to the conclusion that the industrial base in manufacturing was inadequate to provide for economical production of millimeter wave seekers for the MLRS-TGW. This led to the decision by USDR&E James P. Wade, Jr., to establish the DOD MIMIC program in a letter to the military services and DARPA dated 1 February 1985. During the formulation of the program in 1985-86, three key workshops were held at Redstone Arsenal that are shown in the milestones the evolution of the program itself provided the motivation for a major Manufacturing Technology effort keyed to smart weapon applications that provided several key milestones that have been included in this report.

MILESTONES LEADING TO THE DEPARTMENT OF DEFENSE MICROWAVE AND MILLIMETER MONOLITHIC INTEGRATED CIRCUIT PROGRAM

1930s - The six methods of printing circuits presented in the Burnetti-Curtis paper have their origins in numberous U.S. British and German research efforts and patents dating back to the early 1930s. An example is U.S. Patent 2,136,024 PROCESS AND APPARATUS FOR PRODUCING METALLIC COATINGS ON VARIOUS ARTICLES, filed May 3, 1935, issued Nov 8, 1938

1940-1951 - Shockley had investigated field-effect structures both before and after World War II and concluded that the effect could lead to amplification, and made the first record of a Schottky gate transistor in his laboratory notebook at Bell Labs on 20 February 1940, and filed the original patent for the junction field effect transistor (U.S. Patent 2,744,970) on August 24, 1951.

1948 - Publication of the paper "Printed Circuit Techniques: by Cledo Brunetti and Roger W. Curtis, Proceedings of IRE, January 1948

1947-1948 - The functioning of the transistor was demonstrated to management of Bell Labs on Christmas Eve 1947, but announcement was delayed until June 1948 to gain more understanding of the device and its potential applications.

1952 - First conception of planar fabrication of microwave printed circuits was made by Robert M. Barrett with the introduction of the strip transmission line.

1959 - Jack S. Kilby filed an application for a patent on February 6, 1959, that resulted in U.S. Patent 3,138,743, MINATURE ELECTRONIC CIRCUITS being issued June 23, 1964.

1960s-1970s - Ballistic Research Laboratories conducted a systematic program in the potential applications of millimeter wave technology to missile guidance over this decade that included propagation effects, multipath target signatures, and instrumentation development. This provided some broad bounds for MIMIC hardware development.

1960s - First active array Transmit-Receive module developed by Texas Instruments for the Air Force based in silicon technology under the MERA program.

1965 - A group was formed under Vladimir Gelnovatch in the Army Electronic Components Laboratory at Fort Monmouth to provide a focus for the development of hybrid microwave integrated circuit technology.

1966 - The letter "Schottky-Barrier Field Effect Transistor" was published in Proceedings of IEEE February 1967 by C.A. Mead

1968 - The paper "Computer-Aided Design of Wideband Integrated Microwave Transistor Amplifiers on High Dielectric Substrated" by T.F. Burke and V.G. Gelnovatch was Published in the IEEE Journal of Solid State Circuits, June 1968

1969 - The slot transmission line on a dielectric substrate was reported by S.B. Cohn. "Slot Line Characteristics", IEEE MTT Transactions, Vol 17, No 12, December 1969

1969 - The coplanar waveguide reported by C.P. Wen in "Coplanar Waveguide: A Surface Strip Transmission Line Suitable for Reapproval Gyro-Magnetic Device Applications" IEEE MTT Transactions MTT-17, No. 12, December 1969.

1970 - The Paper "Environmental Effects on Radar and Radiometric Systems at Millimeter Wavelengths" at the Symposium at Polytechnic Institute of Brooklyn March 31, April 1-2, 1970, established the broad bounds on the choice of millimeter wavelengths for smart weapon applications.

1970s - The Electronics Technology and Devices Laboratory conducted a program of development of microelectronics including microwave integrated circuits supporting Army smart munitions development.

1972 - Source Selection on Millimeter Wave Seekers was held at Aberdeen Proving Ground. (Hammond Green). The pioneering work of ET&TL, BRL, MICOM, the Air Force, and Sperry influenced the choice of sensing options for this development.

1975 - Side-by-Side Testing of 35Ghz and 95Ghz Missile Seekers was completed at Redstone Arsenal. (TR-RE-75-39) (Hammond Green)

1976 - MM&T Project 38131 - "Production Methods for Millimeter Wave Radiometric Seeker for Submunition Applications" was developed and submitted for the MM&T budget.

1976 - First known gallium arsenide MMIC was fabricated at Plessey, LTD., by Ray Pengelly and James Turner.

1977 - Manufacturing Methods and Technology Five Year Plan FY-79-83 (Project 38131 above was part of plan)

1978 - U.S. Patent for High Electron Mobility Transistor issued to Dingle, et al, Bell Telephone Laboratories (Patent 4,163,237)

1980 - Contract awarded to Sperry Corporation for MM&T project 3139 on Millimeter Wave Seekers for Terminal Homing, Contract DAAH01-80-C-1977.

1980 - First demonstration of High Electron Mobility transistor by Dingle, et al, University of Illinois.

1981 - Contract awarded to Sperry Corporation for the second phase of MM&T Project 3139 on Millimeter Wave Seekers for Terminal Homing, Contract DAAH01-81-C-B239.

1981 - SPIE Conference on INTEGRATED OPTICS and MILLIMETER and MICROWAVE INTEGRATED CIRCUITS held 16-19 November 1981, Von Braun Civic Center, Huntsville, Alabama (SPIE Volume 317, November 16-19, 1981)

1981 - An outline of a structured MIMIC program analogous to VHSIC was presented at the above conference entitled: "Potential of Integrated Optics and Millimeter and Microwave Integrated Circuits for Future MICOM Systems".

1982 - Sperry Gyroscope Corporation submitted the final report "Manufacturing Methods and Technology for Millimeter Seekers for Terminal Homing" MM&T Project 3139, January 1982 (conclusion was millimeter seekers cost 10 times too much).

1983 - Sperry Gyroscope Corporation submitted the final report on Phase II of "Manufacturing Methods and Technology (MM&T) Project for Millimeter Wave Seekers" in February 1983 (MM&T Project 38131).

1983 - "Government Systems and GaAs Monolithic Components" RCA Review Vol 44, p-507, 1983 by Kenneth Sleger December 1983. This paper provided a global view of MIMIC systems and technology for military applications .

1984 - Technical Requirements for a follow-on phase to the Sperry Contract were developed and issued. The project was canceled just short of contract award in a restructuring of MM&T by the Under Secretary of the Army.

1984 - IR&D industrial base analysis performed at Redstone Arsenal on millimeter wave integrated circuit analysis submitted to USDRE as part of document request in August 1984. Results showed about 40 firms working in MIMIC and MIC (hybrids) but little manufacturing process development was being done.

1984 - As follow-up to the above analysis, a task was issued from MICOM through the Guidance and Control Information Analysis Center (GACIAC) to perform a more detailed industrial base analysis on MIC and MIMIC as an amendment to a solicitation dated 30 July 1984. (This was performed by Naresh C. Deo and Peter P. Toulious and published as "State-of-the-Art Review of Microwave and Millimeter Wave Monolithic Integrated Circuits" 1985).

1984 - Seminar conducted at Harry Diamond Laboratories on Millimeter Wave Standards and Measurements Requirements, March 1984.

1984 - The IEEE Society for Microwave Theory and Techniques formed the Committee to Promote National Measurement Standards chaired by Doug Rytting of Hewlett-Packard.

1984 - A proposal for an Army wide "A Structured Program in Microwave and Millimeter Circuit Technology for Smart Munitions" August 1984, was submitted to the Army Materiel Command, after coordination with Picatinny Arsenal and the Army Electronics Technology and Devices Laboratory. The document outlined an Army-wide plan for 38 million dollars.

1984 - A request was made of the Advanced Sensors Directorate by the Office of Under Secretary of Defense (James Wade) in August 1984 for cost and technical data the MICOM had developed on the subject of producibility of millimeter wave seekers (Telephone request).

1984 - In response to the above request, the proposal submitted to the Army was expanded into a document "IMPROVING THE AVAILABILITY, AFFORDABILITY, AND PRODUCIBILITY OF MICROWAVE AND MILLIMETER CIRCUIT TECHNOLOGY" and submitted to USDRE as part of the document request in August 1984. The plan outlined a DOD-wide program for 100 million dollars. Also included in the package was the result of the IR&D industrial base analysis.

1984 - First draft of "Technological Status Microwave and Millimeter Wave Integrated Circuits" completed and submitted in September 1984 under the task order from MICOM, GACIAC-SR-84-07.

1984 - On 28 September 1984, the lack of maturity of Millimeter Wave Technology was a topic of discussion at the DSARC for MLRS-TGW. As a result, the Assistant Secretary of Defense (ASD), (Acquisition Management), asked the Product Engineering Services Office (PESO) to look into the state-of-the-art of millimeter wave components.

1984 - A preliminary assessment of millimeter and microwave monolithic integrated circuit technology was given to the Acting USDRE on 11 December 1984. The same briefing was given to the Service Secretaries and DARPA.

1984 - The Concept Definition Phase of the international program, MLRS-TGW began in November 1984.

1984 - 11 Decenber 1984 - Dr. Robert Heaston briefed USDRE James P. Wade, Jr., on the work of the M^3I Committee

1985 - 5 January 1985 - As a result of the questions raised about the state of the art of millimeter wave technology in conjunction with the MLRS-TGW DSARC, Dr. Robert Heaston prepared correspondence for the signature of James Wade, Under Secretary of Defense (R&E), to the Service Assistant Secretaries for Research and Development and DARPA, requesting that they designate two technical experts to serve on the M3I Committee chaired by Dr. Robert Heaston.

1985 - 1 February 1985 - USDRE James P. Wade, Jr., sent a letter to the Assistant Secretaries of the military services and DARPA on "OSD Microwave/Millimeter Monolithic Technology Initiative"

1985 - 11 February 1985 - Dr. Robert Heaston and Mr. Neal Sullivan prepared a POTENTIAL THRUST AREA on Monolithic Microwave and Millimeter Wave Initiative summarizing objectives of the initiatives.

1985 - 24-26 February 1985 - The U.S. Army Technology and Devices Laboratory served as host for the U.S. Army Gallium Arsenide Workshop with participants from industry TRADOC and Army Labs. Applications on EW, radar, communications and smart weapons were discussed.

1985 - GaAs Monolithic for Affordable Military Systems" by Kenneth Sleger, Journal of Electronic Defense p-27, August 1985. An excellent global view of MIMIC for military application.

1985 - 5 March 1985 - Mr. E.D. Maynard, Jr., prepared "GaAs MMIC Technology Initiative" and presented to the kick-off meeting of the M3I Committee.

1985 - 18-19 March 1985 - The M3I Committee held a workshop at Georgia Institute of Technology with representatives of the three services to discuss potential programs in MIMIC to meet service requirements.

1985 - 26 March 1985 - James S. Kesperis, U.S. Army Electronics Technology and Devices Laboratory, responded to Dr. Heaston's request at the meeting the M3I Committee meeting at Georgia Tech on 18 March 1982 to prepare material on Ultra-High Speed Microelectronics (digital gallium arsenide).

1985 - Seminar on Millimeter Wave Measurements and Standards Requirements held at U.S. Army Harry Diamond Laboratories April 1985.

1985 - On 26 April 1985 Sonny Maynard briefed the Acting DUSD (R&AT), Colonel Carter, on "The GaAs Situation and Program Proposal."

1985 - 9 May 1985 - Mr. E.D. Maynard, Jr., Director of the VHSIC Program, sent a Memorandum to the Deputy Under Secretary of Defense for Research and Advanced Technology DUSD (R&AT) recommending that an OSD initiative be mounted in M3I. Maynard noted that as a result of a DUSD Briefing (AM) to USDRE on DSARCII assessment of MLRS/TGW, DUSD (R&AT) was asked by Dr. Wade to look into the manufacturing options for the MLRS/TGW 94Ghz submunitions seeker electronics.

1985 - In the above letter dated 9 May 1985, to the DUSD (R&AT), E.D. Maynard, Jr., concurred in some points on the work of the work of the M3I Committee but objected to others. He offered recommendations of his own.

1985 - 14 May 1985 - A meeting of the M3I committee was held at the Georgia Institute of Technology.

1985 - 10 June 1985 - Mr. E.D. Maynard, Jr. briefed USDRE on Monolithic Microwave/Millimeter Wave Initiative that included a summary of current gallium arsenide monolithic funding, application of the technology, and deficiencies.

1985 - September - Monolithic Microwave and Millimeter Wave Initiative (M3I) Summary published (Findings and Recommendations of M3I Committee). GACIAC Special Report SR-85-14.

1985 - 5-6 November 1985 - The 1985 Conference on Producibility of Microwave and Millimeter Wave Integrated Circuits was held at Redstone Arsenal. In the introductory talk outlining the MIMIC program, E.D. Maynard, Jr., noted that the DOD MIMIC program was formulated in response to the concerns of the smart weapons community about the high cost of millimeter wave seekers. (See PROCEEDINGS OF THE 1985 CONFERENCE ON PRODUCIBILITY OF MICROWAVE AND MILLIMETER CIRCUITS, 5-6 November 1985).

1985 - December - The Committee on Critical Materials (formed from the Board on Army Science and Technology and the National Materials Advisory Board) was briefed at Redstone Arsenal on MM&T Projects involving electronic, electro-optical and electro-magnetic materials completed and planned. Committee members expressed concern about the status of gallium arsenide technology compared to that in Japan. (See ACHIEVING LEADERSHIP IN MATERIALS TECHNOLOGY FOR THE ARMY OF THE FUTURE 1986).

1986 - Mr. E.D. Maynard, Jr. was appointed MIMIC Program Director.

1986 - Dr. Eliot Cohen, Navy Director of the VHSIC program was recruited to be the Deputy Director of the MIMIC program.

1986 - Service program directors for MIMIC were appointed:
CG Thornton, Army Electronic Technology and Devices Laboratory;
D. McCoy, Office of Assistant Secretary of the Navy for Research Engineering and Systems;
W.J. Edwards. Air Force Wright-Aeronautical Laboratories.

1986 - MIMIC Phase 0 BAA prepared, modified in August 1986.

1986 - Phase 0 MIMIC BAA Issued in October 1986.

1986 - 4-5 November 1986 - Conference on Producibility of Millimeter and Microwave Integrated Circuits held at the Redstone Arsenal Post Theatre.

1986 - 6-7 November 1986 - Conference on Millimeter and Microwave Measurement Standards for Miniaturized Systems held at the Redstone Arsenal Post Theatre. (The National Bureau of Standards outlined program to support MIMIC development).

1987 - February - Phase 0 MIMIC Contract Awards made. Completed, February 1988.

1987 - 23 September 1987 - The National Bureau of Standards held Meeting to establish Industrial Consortium for MIMIC Standards, at Gaithersburg, Maryland.

1987 - The paper "W-Band Microstrip Integrated Circuit Transceiver" was published in the Microwave Journal, October 1987 p-115 by Yen, Y.E., English, D., Grote, A., Hayashebarn, G., Pham, T., Nyan, T.C., Yen, P, Wandinger, L., Frerburg, E. This paper pointed the way to W-Band Monolithic Integrated Circuit Transceiver.

1987 - December - Source Selection on MIMIC Phase One was held at NRL. (Jerry Dickson)

1988 - The MIMIC program was transferred to DARPA in September and Dr. Eliot Cohen assumed the role as Director.

1988 - Phase 1 MIMIC contracts awarded in May 1988.

1989 - January issue of MICROWAVE JOURNAL article, "The MIMIC Program: A Technology Inpact Report".

1989 - First Annual MIMIC Conference held at the National Institute of Standards and Technology in Garthersburg MD, in March 1989.

1989 - The Concept Definition Phase of the international MLRS-TGW program was completed. The millimeter wave seeker had been identified as a risk actor, but was deemed moderate enough for the program to enter system demonstration.

1989 - First pseudomorphic High Electron Mobility Transistor (PHEMT) reported by Aust, et al, of TRW.

1990 - The System Demonstration Phase for the International MLRS-TGW program began.

1990 - A four-year MANTECH effort began with TRW on a MICOM contract for 94Ghz MILLIMETER WAVE SEEKER (The goal was to leverage the MIMIC effort to provide delivery of hardware).

1990 - A four-year Manufacturing Technology effort began with TRW on a MICOM contract entitled, "94GHz MILLIMETER WAVE Transceiver" (Jerry Dickson) Goal was to insert MIMIC devices developed by ETDL into the U.S. work share of the MLRS-TGW seeker.

1990 - July - Source selection on MIMIC Phase 2 was held at Evans Field New Jersey. (Jerry Dickson)

1991 - Phase 2 MIMIC began in August 1991.

1992 - The United States withdrew from the international MLRS-TGW program.

1992 - The first W-band active image reject receiver was developed by TRW under the MICOM Manufacturing Technology effort entitled "94GHz Millimeter Wave Transceiver" (Jerry Dickson). The receiver contained a low noise amplifier with an image reject mixer. This module empirically confirmed that the noise figure of the Low Noise Amplifier (LNA) predominantly sets the noise level of the entire system. This 2-channel received, which employed a single LNA for each channel, laid the technology framework for the Longbow KA-Band 2-channel single LNA Cost Reduction received configuration and the BATP3I W-band receiver configuration.

1993 - The first W-band upconverter power amplifier module was developed by TRW under the MICOM Manufacturing Technology effort entitled, "94GHz Millimeter Wave Transceiver" (Jerry Dickson). This module contained two MIMIC power amplifier chips and one driver output chip. This module empirically established that the power amplifier chips (input states) must be driven hard into saturation at room temperature to sustain the required output level at hot temperature. This module replaced the MLRS-TGW GUNN diode amplifier assembly in the W-band transmitter.

1994 - The Manufacturing Technology Division at MICOM performed MIMIC based transceiver and sensor testing in Paris, France. (Jerry Dickson). Results of the MIMIC based transceiver, which was eventually integrated into US residual MLRS-TGW hardware, convincingly demonstrated that the MIMIC based sensor had the best overall performance of the previously 20 built and tested MLRS-TGW sensors.

1995 - Program completed in August 1995. Final Annual Meeting was held August 30 - September 1, 1994 at the Hyatt Regency in Crystal City.

APPENDIX B
A STRUCTURED PROGRAM IN MICROWAVE AND MILLIMETER CIRCUIT TECHNOLOGY FOR SMART MUNITIONS

ROUTING AND TRANSMITTAL SLIP Date 21 June

TO: (Name, office symbol, room number, building, Agency/Post)	Initials	Date
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As Requested	For Correction	Prepare Reply
Circulate	For Your Information	See Me
Comment	Investigate	Signature
Coordination	Justify	

REMARKS

Why are we offering Bob Oswald this (undoubtedly excellent) advice - if we really want him to do some of this, we should start it & allow him to "take it away from us" (ha-ha) -

DO NOT use this form as a RECORD of approvals, concurrences, disposals, clearances, and similar actions

FROM: (Name, org. symbol, Agency/Post)	Room No.—Bldg.
REV, B. Pittman	Phone No. 7778

5041-102

U.S. G.P.O. 1979-285-092

OPTIONAL FORM 41 (Rev. 7-76)
Prescribed by GSA
FPMR (41 CFR) 101-11.206

DEPARTMENT OF THE ARMY
UNITED STATES ARMY MISSILE COMMAND
REDSTONE ARSENAL, ALABAMA 35898-5000

AMSMI-REX

SUBJECT: Proposal for a Structured Program in Microwave and Millimeter Integrated Circuits to Support the Smart Munitions Thrust

Commander
US Army Electronics Research and Development Command
ATTN: AMDEL-CT/Dr. R. B. Oswald
2800 Powder Mill Road
Adelphi, MD 20783

1. We are deeply concerned that emerging technology of microwave and millimeter integrated circuits that would help the Army achieve the goals of affordability, producibility, and packing density for smart munitions does not have sufficient focus to achieve those goals. The present method of resource allocation leaves the research objectives in this area only loosely coupled with the Smart Munition Thrust. To provide some improvement in coupling, the subject proposal would provide a program element for a structured effort that would insure strong correlation between the work in microwave and millimeter integrated circuits and the program needs in smart munitions. This program element would be assigned to MICOM as the lead command for smart munitions.

2. We are exploring the feasibility of additional program elements in infrared sensors and integrated optics for smart munitions that would have the same purpose as the subject proposal.

3. Comments from ERADCOM would be appreciated before the proposal is submitted to the Army Materiel Command.

FOR THE COMMANDER:

1 Encl
Proposal

For use of this label, see AR 340-15; the proponent agency is The Adjutant General's Office.

INITIALS

SIGNATURE or INITIALS marker

DA LABEL 116, 1 Feb 69

PROPOSAL

A STRUCTURED PROGRAM IN MICROWAVE
AND MILLIMETER CIRCUIT TECHNOLOGY
FOR SMART MUNITIONS

AUGUST 1984

US ARMY MISSILE LABORATORY
US ARMY MISSILE COMMAND

OBJECTIVE:

The objective is to conduct a structured VHSIC-like program in microwave and millimeter integrated circuit technology to achieve goals of affordability, producibility, and packing density in support of the Army thrust in smart munitions. There is already in progress some excellent basic work that supports these objectives but is not focused, and program gaps have not been systematically identified as they relate to smart munitions objectives. The underlying premise of the proposed approach is that there are generic elements to the technology common to a number of applications throughout the major subordinate commands of the Army Materiel Command, and a limited family of components and subsystems can be identified through a systematic needs analysis as the basis for the first phase of the program. The effort would include the fabrication of a limited number of these units for laboratory test and evaluation to investigate the relationships between the fabrication processes and performance. The development of a cost model of the manufacturing processes would be part of the first phase as the prelude to a yield enhancement program that would follow.

The advantages of this approach would be: (1) gaps in research, and problems would be discovered that would not otherwise be found; (2) the approach would make more efficient use of RDT&E resources since problem solving would take place on the generic level thus avoiding unwanted duplications of effort; and, (3) some time saving could be achieved by conducting the program off-line to the ongoing programs throughout AMC and then relying on technology insertions. To achieve program objectives would require the realignment of resources in AMC and the establishment a new program line assigned to MICOM under the Lead Laboratory for Smart Munitions.

BACKGROUND:

The application of integrated microwave and millimeter integrated circuit technology in smart munitions will allow the achievement of high packing densities for sensors in small diameter munitions, and permit a shift away from labor-intensive manufacturing technologies to the planar processes of integrated circuit fabrication. The program can thus synergistically couple with the investment being made under the Department of Defense (DOD) Very High Speed Integrated Circuit Program (VHSIC) on advanced lithographic methods, epitaxial materials growth, diffusion, ion implantation, and advanced materials processing.

The potential of millimeter integrated circuits to reduce cost, size, and weight was demonstrated in any analysis conducted during the course of an MM&T program on the seeker shown in Figure 1. With the Assault Breaker millimeter seeker as the baseline, four levels of millimeter technology were examined with the results shown in Figure 2. Although the cost figures are optimistic, the trend is the right direction. An analysis of the seeker showed that nearly 80 percent of the cost was for four components, and a big potential for cost reduction was in the front end. As a result of a redesign of the front

end under the MM&T effort, the parts count was reduced by 37 percent and the data for the "semi-integrated" version in the second line of Figure 2 was produced. Line 3 of Figure 2 is a projection that can be achieved with microwave and millimeter integrated circuits in the near term and the fourth line depicts the ultimate goal of fabricating all the circuit functions, both active and passive in a single substrate material under the monolithic approach.

ELEMENTS OF THE PROGRAM

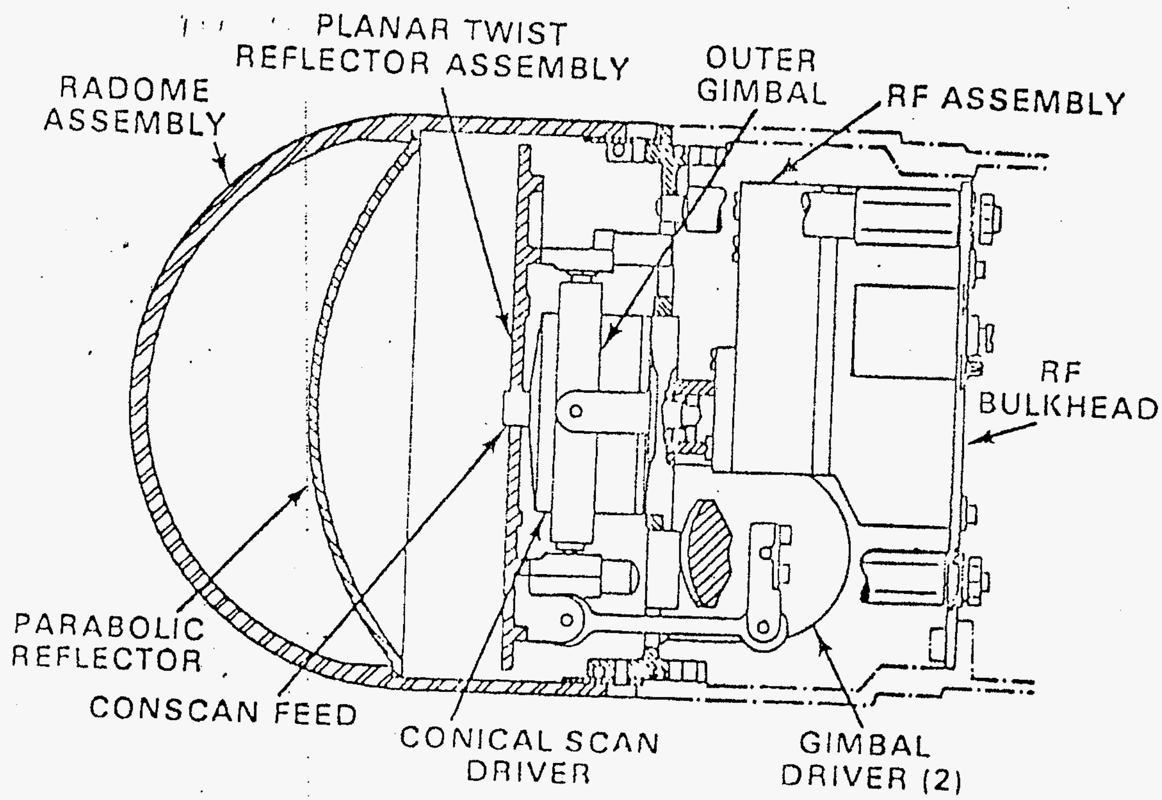
The first step will be to identify an array of needs from an analysis of the programs throughout the major subordinate commands of AMC that may include programs in exploratory development through fielded systems. This array of needs will generate a set of technical constraints that will then be applied to the array of available microwave and millimeter wave integrated circuits technologies. Figure 3 illustrates five of these technologies and Figure 4 summarizes the salient characteristics of each. Each of the approaches illustrated in Figure 3 provides a transmission line technology that is adaptable to batch manufacturing that can incorporate both passive and active functions to provide microwave and millimeter subsystems, each with its own distinctly different set of problems in achieving an integrated subsystem design as shown in Figure 4.

By filtering these candidate technologies through the needs, not only will leading technologies emerge, but gaps in research will be uncovered that would remain undiscovered under the present method for allocating resources for this area. Without the proposed approach, the transfer of these technologies into systems is painfully slow. The examination of microwave integrated circuit technology is part of the Army Missile Laboratory program in digital beam-forming, and also an MM&T program for a 94 GHz integrated transceiver that is coordinated with the ET&D Laboratory, but these are the exceptions rather than the rule. The potential cost advantage of these technologies may be lost for some applications if it is necessary to design expensive transitions to conventional wave guide plumbing, but this problem will never be uncovered in the first place without the systematic analysis of the technologies against program needs. For a sensor system for target recognition, the specification for a high purity waveform may pose a problem in choosing the technology that minimizes the dispersion, but again the problem must be uncovered and examined in a systematic way against the specific application.

The choice of the specific technologies for subsystem development will be done in design studies lasting six months. Each performer in the program would be free to make his own choices of the particular technologies, materials, processes, and technical approaches to integration, thus providing a spur to innovation that would not be present in the current method of technology transfer. The development, test and evaluation phase following this would include the development of a cost model for the fabrication process as the basis for allocating funds for the yield enhancement program. Technology insertion programs and manufacturing technology efforts would be developed for funding under separate program elements. The proposed program element would also include unstructured research on electronic materials and materials growth and characterization. The overall program schedule is summarized in Figure 5.

REF: 7[illegible]-84

MILLIMETER WAVE SEEKER HEAD



FOCUS OF MM&T

- o IMPROVED ASSEMBLY
- o AUTOMATED INSPECTION
- o AUTOMATED TEST EQUIPMENT
- o CHANGES IN MATERIALS, FINISH, TOLERANCE AND GEOMETRY

FIGURE 1

COST COMPARISONS FOR THE FRONT END

OF A W-BAND FM-CW MILLIMETER SEEKER

TECHNOLOGY TYPE	UNIT PRODUCTION COST ESTIMATE	RELATIVE VOLUME (CUBIC INCHES)	PRODUCTION AVAILABILITY
DISCRETE COMPONENT	$14,000	26	1978
SEMI-INTEGRATED (REDESIGNED BASE UNIT)	6,500	9	1979
FULLY-INTEGRATED	2,300	6	1984
MONOLITHIC	900	1	1986-88

FIGURE 2

TRANSMISSION LINE TECHNOLOGIES FOR HYBRID MICROWAVE AND MILLIMETER WAVE

CIRCUIT TECHNOLOGIES

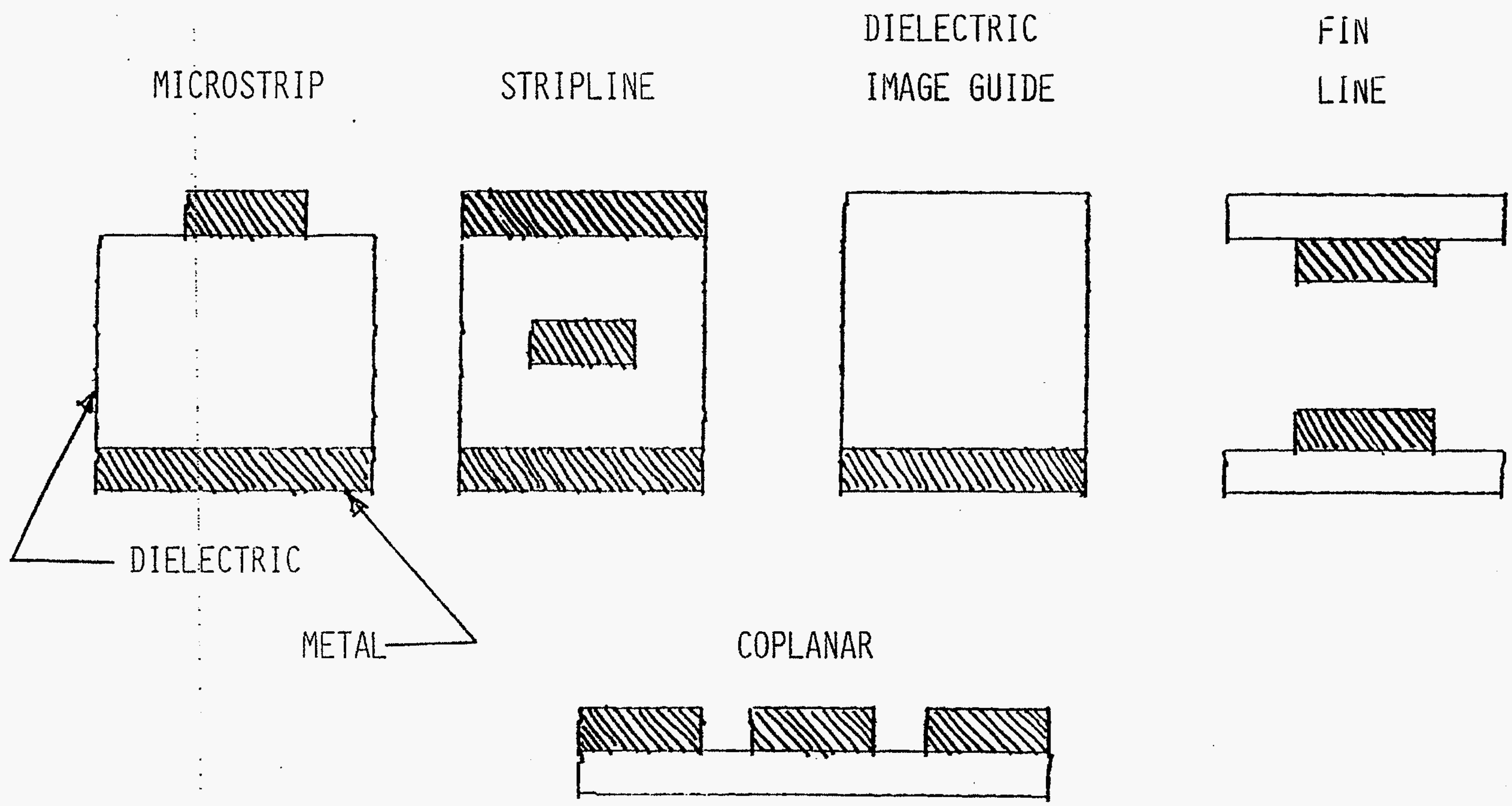


FIGURE 3

COMPARISON OF MICROWAVE AND MILLIMETER WAVE INTEGRATED CIRCUIT APPROACHES

CHARACTERISTICS	MILLIMETER INTEGRATED CIRCUIT MEDIA				
	MICROSTRIP	STRIPLINE	DIELECTRIC IMAGE GUIDE	FIN LINE	COPLANAR-WAVE GUIDE
TRANSMISSION LOSS	MEDIUM	HIGH	LOWEST	LOW	HIGH
FREQUENCY OF OPERATION (GHZ)	UP TO 100	30-100	BEYOND 70	30-100	UP TO 20
CHARACTERISTIC IMPEDANCE RANGE ( )	20-125	40-120	25	10-400	40-150
RADIATION LOSS	LOW	LOW	MEDIUM	LOW	HIGH
DISPERSION, MULTIMODING	LOW DISPERSION, POTENTIALLY MULTIMODED	LOW DISPERSION	DISPERSIVE, OFTEN HEAVILY MULTIMODED	DISPERSIVE, POTENTIALLY MULTIMODED	DISPERSIVE, MULTIMODED
ACTIVE AND PASSIVE DEVICE COMPATABILITY AND INTEGRABILITY 1) SHUNT MOUNTED	DIFFICULT	EASY	DIFFICULT	EASY	EASY
2) SERIES COST	EASY LOW COST	EASY MODERATE COST	DIFFICULT MODERATE COST	EASY LOW COST	EASY LOW COST

FIGURE 4

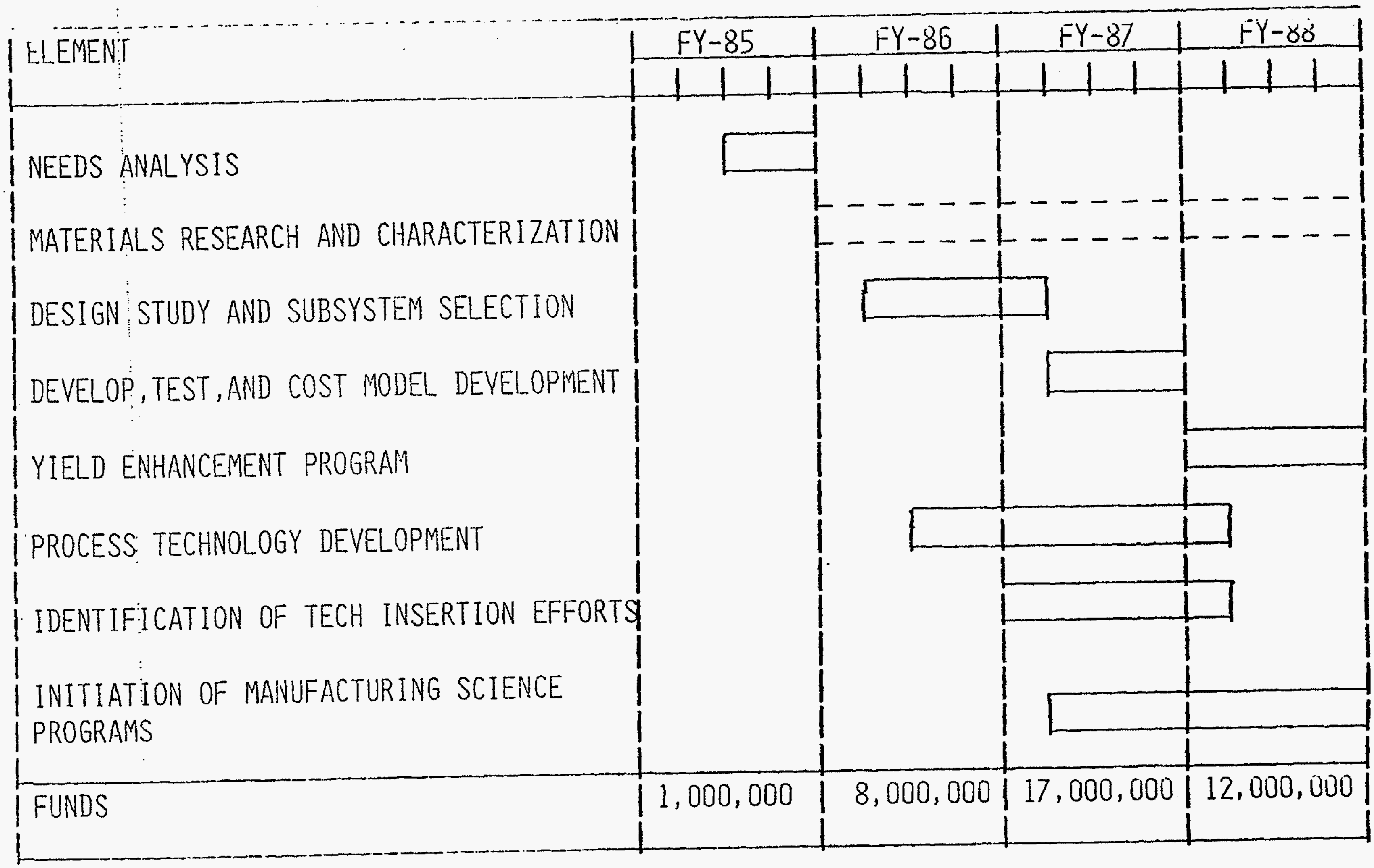

ELEMENT
FY-85
FY-86
FY-87
FY-88
NEEDS ANALYSIS
MATERIALS RESEARCH AND CHARACTERIZATION
DESIGN STUDY AND SUBSYSTEM SELECTION
DEVELOP,TEST,AND COST MODEL DEVELOPMENT
YIELD ENHANCEMENT PROGRAM
PROCESS TECHNOLOGY DEVELOPMENT
IDENTIFICATION OF TECH INSERTION EFFORTS
INITIATION OF MANUFACTURING SCIENCE PROGRAMS
FUNDS
1,000,000
8,000,000
17,000,000
12,000,000

FIGURE 5

DEPARTMENT OF THE ARMY
UNITED STATES ARMY MISSILE COMMAND
REDSTONE ARSENAL, ALABAMA 35898

DRSMI-REX

SUBJECT: The Need for VHSIC-Like Programs in Infrared Detectors and Millimeter and Microwave Integrated Circuits

Commander
US Army Electronics Research and Development Command
ATTN: DRDEL-CT, Dr. R. B. Oswald
2800 Powder Mill Road
Adelphi, Maryland 20783

1. The progress being made in the advanced fabrication technologies for the Department of Defense (DOD) Very High Speed Integrated Circuit (VHSIC) program can have a synergistic coupling with other emerging technologies that are vital to the achievement of the goals of affordability in the Army thrust on smart munitions. Manufacturing cost analyses performed under the Missile Command (MICOM) Manufacturing Methods and Technology (MM&T) projects have shown that by shifting from labor-intensive manufacturing processes currently used in fabricating microwave and millimeter sensors to the planar processes of integrated circuit technology, large reductions in the per unit production cost can be achieved. It is, therefore, suggested that the Electronics Research and Development Command (ERADCOM) consider the feasibility of VHSIC-like programs in infrared detector arrays and microwave and millimeter integrated circuit technology to serve the needs of all the major subordinate commands.

2. This investment strategy would begin with the recognition that there are generic elements to these technologies common to a number of applications that could provide the basis for structured programs analogous to VHSIC. Under this approach, limited families of components and subsystems would be chosen from an application analysis to be pursued in the first phase of the program. This would include fabrication of a limited number of these units for laboratory test and evaluation to investigate the relationships between the fabrication processes and performance. The development of a cost model of the manufacturing processes would be part of this first phase as a prelude to a yield enhancement program that would follow.

3. The advantages of this approach would be: (a) gaps in research and problems would be discovered that would not otherwise be found; (b) the approach would make more efficient use of Research, Development, Test, and

Evaluation (RDT&E) resources since problem-solving would take place on the generic level, thus avoiding unwanted duplication effort; and (c) some time-saving could be achieved by conducting the programs off-line to the ongoing RDT&E efforts and then relying on technology insertion as is being done in VHSIC. The availability of a credible data base on cost, yield, and producibility would also provide the Government better control over downstream acquisition costs in major weapon acquisition programs.

4. An essential element of such programs must be the improvement in availability and cost of the underlying materials technology. The Army Missile Laboratory (AML) is already working with the Night Vision and Electro-Optics Laboratory (NV&EOL) to improve the quality of cadmium telluride substrates for the fabrications of mercury cadmium telluride detectors by the liquid phase epitaxy process. There are also a number of actions that need to be taken to improve the cost and availability of millimeter wave substrate materials including sapphire, quartz, alumina, and duroid.

5. An applications analysis is recommended for the FY 85 ERADCOM program that would provide, in matrix form, the potential technologies keyed to the applications of the major subordinate commands.

FOR THE COMMANDER:

APPENDIX C
IMPROVING THE AVAILABILITY, AFFORDABILITY, AND PRODUCIBILITY OF MICROWAVE AND MILLIMETER CIRCUIT TECHNOLOGY FOR SMART MUNITIONS

2/28/85

RFF: 160-85

IMPROVING THE AVAILABILITY, AFFORDABILITY, AND PRODUCIBILITY OF MICROWAVE AND MILLIMETER CIRCUIT TECHNOLOGY FOR SMART MUNITIONS

AUGUST 1984

US ARMY MISSILE LABORATORY

US ARMY MISSILE COMMAND

OBJECTIVE:

The basic assumption under this proposed program is that availability, affordability, and producibility of microwave and millimeter integrated circuits cannot be achieved within the framework of individual programs such as MLRS-TGW or the new Air Force follow-on to WASP even with supporting MM&T efforts throughout DOD. Although there is a large industry IR&D effort in this area (370 man years in FY84) very little of this is devoted to establishing a design base for the technology, and the manufacturing processes for cost effective production and tests of microwave and millimeter integrated circuits. The latter effort requires substantial capital investments that are beyond the threshold of individual MM&T efforts and which industry will not allocate out of IR&D.

The objective therefore is to conduct a structured VHSIC-like program in microwave and millimeter integrated circuit technology to achieve goals of affordability, producibility, and packing density in support of the Army thrust in smart munitions. By structured program is meant an array of activities from basic research through producibility engineering, manufacturing technology and technology insertion that are keyed to a specific set of subsystems. There is already in progress some excellent basic work that supports these objectives but it is not focused, and program gaps have not been systematically identified as they relate to smart munitions objectives. The underlying premise of the proposed approach is that there are generic elements to the technology common to a number of applications throughout the major subordinate commands of the Army Materiel Command, and a limited family of components and subsystems can be identified through a systematic needs analysis as the basis for the first phase

of the program. The effort would include the fabrication of a limited number of these units for laboratory test and evaluation to investigate the relationships between the fabrication processes and performance. The development of a cost model of the manufacturing processes would be part of the first phase as the prelude to a yield enhancement program that would follow.

The advantages of this approach would be: (a) gaps in research, and problems would be discovered that would not otherwise be found; (b) the approach would make more efficient use of RDT&E resources since problem solving would take place on the generic level thus avoiding unwanted duplications of effort; and, (c) some time saving could be achieved by conducting the program off-line to the ongoing programs throughout AMC and then relying on technology insertions. To achieve program objectives would require the realignment of resources in AMC and the establishment of a new program line assigned to MICOM under the Lead Laboratory for Smart Munitions.

BACKGROUND:

The application of integrated microwave and millimeter integrated circuit technology in smart munitions will allow the achievement of high packing densities for sensors in small diameter munitions, and permit a shift away from labor-intensive manufacturing technologies to the planar processes of integrated circuit fabrication. The program can thus synergistically couple with the investment being made under the Department of Defense (DOD) Very High Speed Integrated Circuit Program (VHSIC) on advanced lithographic methods, epitaxial materials growth, diffusion, ion implantation, and advanced materials processing.

The potential of millimeter integrated circuits to reduce cost, size, and weight was demonstrated in an analysis conducted during the course of an MM&T

program on the seeker shown in Figure 1. With the Assault Breaker millimeter seeker as the baseline, four levels of millimeter technology were examined with the results shown in Figure 2. Although the cost figures are optimistic, the trend is the right direction. An analysis of the seeker showed that nearly 80 percent of the cost was for four components, and a big potential for cost reduction was in the front end. As a result of a redesign of the front end under the MM&T effort, the parts count was reduced by 37 percent and the data for the "semi-integrated" version in the second line of Figure 2 was produced. Line 3 of Figure 2 is a projection that can be achieved with microwave and millimeter integrated circuits in the near term and the fourth line depicts the ultimate goal of fabricating all the circuit functions, both active and passive, in a single substrate material under the monolithic approach.

STRONGER DESIGN BASE NEEDED:

A strong design base is a prerequisite to undertaking a program in improved manufacturing processes. The design process must begin with the specifications of the subsystem that the millimeter or microwave circuit must meet within the system, then alternative ways of distributing the different electromagnetic functions in integrated circuit form to meet the specifications must be examined within the available constraints of device physics and the available manufacturing processes. The different electromagnetic functions in close proximity will result in interaction between the different circuit elements that makes the problem of establishing and applying physical models extremely difficult, since physical models of individual circuits must be modified by these interaction effects. Part of the process of establishing the base for analysis and design must therefore be to develop approximation techniques that allow the application of high speed computers.

By focusing the design effort on a limited family of generic components and subsystems identified in the needs analysis, maximum creativity can be brought to bear on the problem solving. This family of generic components and subsystems may include several of the hybrid technologies as well as monolithic depending on the program schedules and maturity of the different technology options, ranging in frequency from 30 to 100 GHz. The individual components and subsystems may include receivers, transceivers, amplifiers, digital beamforming modules and others. The packaging of this portion of the program would allow participation of universities, millimeter and microwave components houses as well as the Government laboratories and other contractors.

DEFICIENCIES IN CURRENT MANUFACTURING METHODS:

The current manufacturing processes for Gunn, varactor, IMPATT and mixer diodes for integration with microstrip or one of the other hybrid technologies are highly labor intensive and performed by engineers and scientists. Efforts are needed not only to automate the manufacturing processes, but to design the individual components for easy integration with the appropriate transmission technology. Current methods for bonding of individual millimeter components with the transmission medium requires an accuracy not found in the currently available pick-and-place equipment. Tuning millimeter wave circuits after fabrication is highly labor intensive and therefore costly. The application of automatic laser trimming equipment to make cuts in the microstrip while simultaneously monitoring performance is one alternative for solving this problem. Some efforts to achieve solutions to these problems are in progress under Army MM&T programs, but the full range of problems to be solved and the capital investment costs are too high for the relatively small individual MM&T

efforts. Also, very little is being done by industry on these problems under industry IR&D.

To establish a firm manufacturing base in microwave and millimeter integrated circuits will also require a well-established measurements standards and reliable test, measurements, and diagnostic equipment for the production of microwave and millimeter integrated circuits, and the investment level is such that the objectives cannot be achieved under individual MM&T efforts or major programs such as MLRS-TGW, but only under a service-wide or DOD-wide program. There is currently available on the market, laboratory instrumentation for measuring fundamental signal parameters such as power, frequency, signal spectrum, and noise of millimeter circuits, but the need here is the specialized production test instrumentation that reduces the labor-intensiveness of the overall process. Again, some limited efforts have been done on DOD contracts. For example, Rome Air Development Center sponsored a contract to establish a detailed approach to cost effective automatic test procedures for monolithic microwave integrated circuits, but much more must be done. Recently published data shows that 46% of the total fabrications cost of millimeter integrated circuits for direct broadcast satellite receivers was in production testing.

MONOLITHIC TECHNOLOGY:

Figure 3 illustrates five of the transmission technologies for the hybrid options, and Figure 4 summarizes the different set of problems in achieving an integrated subsystem in each of these options. Farther in the future, both active and passive components may be fabricated in a single substrate to yield a monolithic subsystem such as a transceiver, but many difficult problems must be solved before that can be achieved. The process technology for gallium arse-

nide is the most advanced for this application and Gunn oscillators have been fabricated in gallium arsenide. However, Gunn oscillators yield higher power in indium phosphide, but unfortunately the technology of indium phosphide is much farther behind that of gallium arsenide. The sharply different doping profiles required of the different circuit elements in the monolithic technology poses a difficult technical challenge that must be met before monolithic circuits can be realized. Monreciprocal circuit elements will also be difficult to achieve in monolithic technology, and there is still much research to be done in radiating elements. Monolithic technology is lagging the hybrid technologies by at least 5 years.

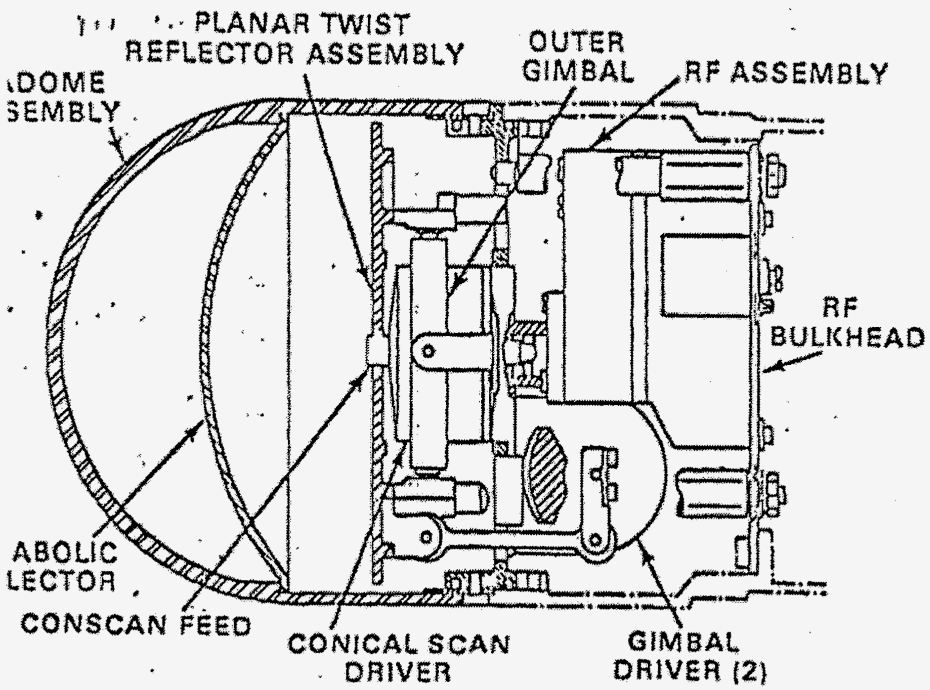
ELEMENTS OF THE PROGRAM:

The first step will be to identify an array of needs from an analysis of the programs throughout the major subordinate commands of AMC that may include programs in exploratory development through fielded systems. This array of needs will generate a set of technical constraints that will then be applied to the array of available microwave and millimeter wave integrated circuits technologies. Figure 3 illustrates five of these technologies and Figure 4 summarizes the salient characteristics of each. Each of the approaches illustrated in Figure 3 provides a transmission line technology that is adaptable to batch manufacturing that can incorporate both passive and active functions to provide microwave and millimeter subsystems, each with its own distinctly different set of problems in achieving an integrated subsystem design as shown in Figure 4.

By filtering these candidate technologies through the array of needs, not only will leading technologies emerge, but gaps in research will be uncovered

REF: 766-84

MILLIMETER WAVE SEEKER HEAD



FOCUS OF MM&T

- o IMPROVED ASSEMBLY
- o AUTOMATED INSPECTION
- o AUTOMATED TEST EQUIPMENT
- o CHANGES IN MATERIALS, FINISH, TOLERANCE AND GEOMETRY

FIGURE 1

COST COMPARISONS FOR THE FRONT END
OF A W-BAND FM-CW MILLIMETER SEEKER

TECHNOLOGY TYPE	UNIT PRODUCTION COST ESTIMATE	RELATIVE VOLUME (CUBIC INCHES)	PRODUCTION AVAILABILITY
DISCRETE COMPONENT	$14,000	26	1978
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MONOLITHIC	900	1	1986-88

FIGURE 2

TRANSMISSION LINE TECHNOLOGIES FOR HYBRID MICROWAVE AND MILLIMETER WAVE CIRCUIT TECHNOLOGIES

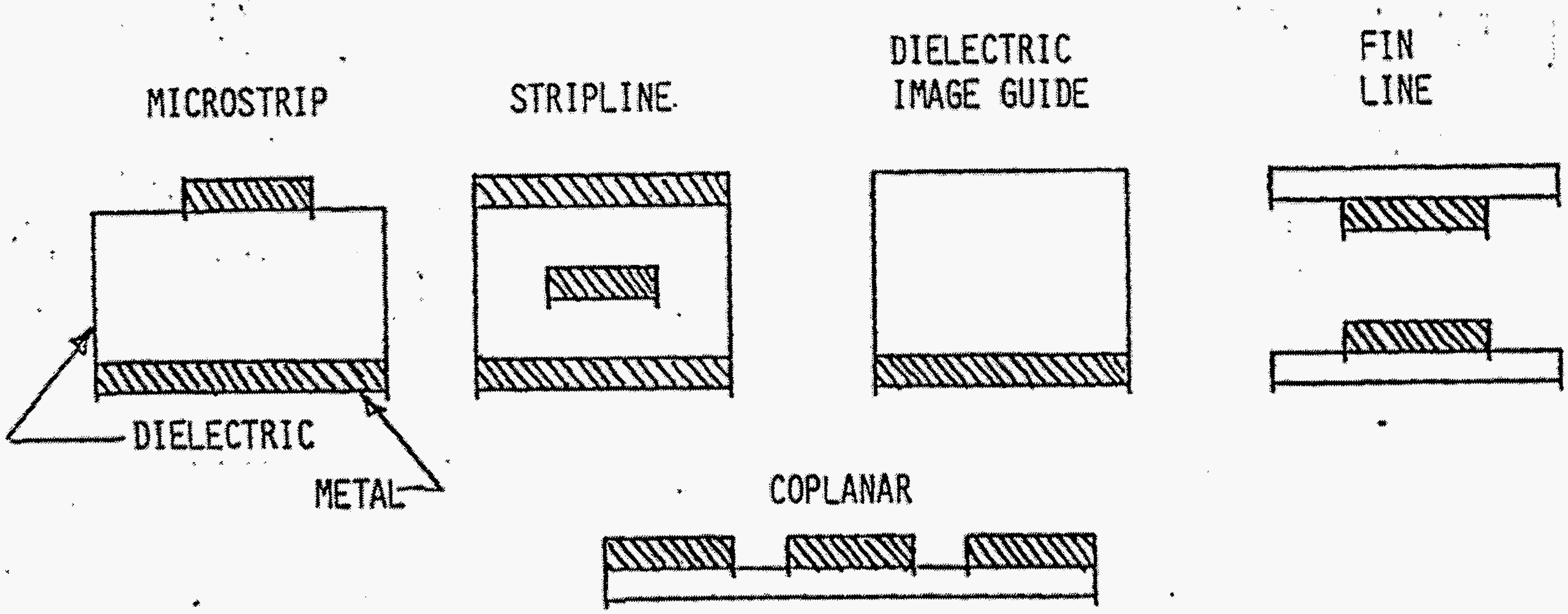

FIGURE 3

COMPARISON OF MICROWAVE AND MILLIMETER WAVE INTEGRATED CIRCUIT APPROACHES

CHARACTERISTICS	MILLIMETER INTEGRATED CIRCUIT MEDIA				
	MICROSTRIP	STRIPLINE	DIELECTRIC IMAGE GUIDE	FIN LINE	COPLANAR-WAVE GUIDE
TRANSMISSION LOSS	MEDIUM	HIGH	LOWEST	LOW	HIGH
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CHARACTERISTIC IMPEDANCE RANGE ( )	20-125	40-120	26-	10-400	40-150
RADIATION LOSS	LOW	LOW	MEDIUM	LOW	HIGH
DISPERSION, MULTIMODING	LOW DISPERSION, POTENTIALLY MULTIMODED	LOW DISPERSION	DISPERSIVE, OFTEN HEAVILY MULTIMODED	DISPERSIVE, POTENTIALLY MULTIMODED	DISPERSIVE, MULTIMODED
ACTIVE AND PASSIVE DEVICE COMPATABILITY AND INTEGRABILITY 1) SHUNT MOUNTED	DIFFICULT	EASY	DIFFICULT	EASY	EASY
2) SERIES	EASY	EASY	DIFFICULT	EASY	EASY
COST	LOW COST	MODERATE COST	MODERATE COST	LOW COST	LOW COST

FIGURE 4

ELEMENT	FY-85	FY-86	FY-87	FY-88
NEEDS ANALYSIS				
MATERIALS RESEARCH AND CHARACTERIZATION				
DESIGN STUDY AND SUBSYSTEM SELECTION				
DEVELOP, TEST, AND COST MODEL DEVELOPMENT				
YIELD ENHANCEMENT PROGRAM				
PROCESS TECHNOLOGY DEVELOPMENT				
IDENTIFICATION OF TECH INSERTION EFFORTS				
INITIATION OF MANUFACTURING SCIENCE PROGRAMS				
FUNDS	2,000,000	16,000,000	34,000,000	25,000,000

FIGURE 5

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